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REPOSITORY NEAR-FIELD THERMAL MODELING UPDATEINCLUDING ANALYSIS OF OPEN MODE DESIGN CONCEPTS - DRAFT REV. M

H. R. Greenberg, M. Sutton, M. Sharma, A. V. Barnwell

August 10, 2012

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Lawrence Livermore National Laboratory

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REVISION HISTORY

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- Original document.

Table of Contents

List of Tables

LIST OF FIGURES

ACRONYMS

ANL	Argonne National Laboratory
BSC	Bechtel-SAIC Co.
BWR	Boiling Water Reactor
DOE	U.S. Department of Energy
EBS	Engineered Barriers System
FY	Fiscal Year
GWd	Gigawatt days
GWd/MT	Gigawatt (thermal) - days per metric ton
GWe	Gigawatts electric
GWt	Gigawatts thermal
LLNL	Lawrence Livermore National Laboratory
MT	Metric Ton (used as an abbreviation for MTHM, MTIHM, and MTU)
MTHM	Metric Tons of Heavy Metal
MTIHM	Metric Tons of Initial Heavy Metal
MTU	Metric Tons of Uranium
NE	DOE-Nuclear Energy
ORNL	Oak Ridge National Laboratory
PWR	Pressurized Water Reactor
SNFA	Spent Nuclear Fuel Assembly
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
UFD	Used Fuel Disposition
UNF	Used Nuclear Fuel
UOX	Uranium Oxide Fuel
WF	Waste Form
WP	Waste Package
YMP	Yucca Mountain Project

NOMENCLATURE AND SYMBOLS

α	thermal diffusivity, $m^2/s = k/(\rho \cdot C_p)$
A	area, m^2
C_p	specific heat, kJ/kg-K
ε	emissivity, dimensionless (subscripts i and o are used to denote inner and outer surface emissivities)
h	convection coefficient, $W/(m^2\text{-}K)$
k, k_{th}	thermal conductivity, W/(m-K)
q	heat, W
q_A	heat per unit area, W/m^2
q_L	heat per unit length, W/m
r	radius, m
r_i	radius of the inner cylinder, m
r_o	radius of the outer cylinder, m
R	thermal resistance, $(m^2\text{-}K)/W$
σ	Stefan Boltzmann constant = $5.670 \cdot 10^{-8}$ W/ $(m^2\text{-}K^4)$
t	time, s
T	temperature, °C
T_{store}	surface storage time, yr
V_{dur}	ventilation duration
V_{eff}	ventilation efficiency

1. EXECUTIVE SUMMARY

Open and Enclosed Repository Design Concepts

The FY11 disposal concepts report: *Generic Repository Design Concepts and Thermal Analysis* (FY11), recognized open and enclosed emplacement modes, and recommended further work to evaluate one or more open modes (Hardin et al. 2011, Section 6). Enclosed modes were defined to include disposal concepts that call for waste packages to be in direct contact with any surrounding solid medium such as buffer material, backfill, or host geology. For enclosed modes, the direct contact begins immediately at emplacement or shortly thereafter, with that contact influencing peak near-field temperature. Open modes maintain unsaturated, air-filled open spaces around the waste packages for some time prior to permanent closure, and even after closure for some concepts.

This report evaluates open modes for clay and alluvium (alluvium is used as an example for sedimentary rock). Sandia National Laboratories (SNL) have performed a preliminary assessment of a hybrid open mode concept for a salt repository design, with separate ventilation tunnels between emplacement alcoves, using finite element analysis codes, and therefore the analysis for the salt repository design concept is not evaluated here. As discussed in Section 2.5 of *Design Concepts/Thermal Load Management Summary* (Hardin et al. 2012), crystalline rock (such as granite) was not considered to be a good candidate for open mode repository design concepts.

Changes in the Analytical Model to Accommodate Open Mode Concepts

This report uses a modified version of the analytical model solution developed in Sutton et al. 2011, plus additional modeling, documented in Appendix A, which includes:

- A radiation heat transfer model for the open air space prior to backfill, based on infinite concentric cylinders
- A ventilation system model with a selectable fixed value for the ventilation thermal efficiency, and with a selectable operating time
- A short period (10 yr) during which radiation continues, but ventilation ceases, as closure operations are conducted
- A backfill thermal conduction model replacing the radiation model after backfill has been added (i.e., after closure)
- The addition of decay heat data for UOX spent nuclear fuel with an average burnup of 40 GWd/MT (more representative of the existing fuel inventory than the 60 GWd/MT used previously, which is more representative of emerging and future fuel inventory)

The Suite of Base Case Models Evaluated

A suite of base case models is defined in Section 3.2.1 covering the following combination of input parameters:

- Commercial LWR UOX spent nuclear fuel, with burnup values of 40 GWd/MT and 60 GWd/MT
- Waste package sizes of 4, 12, 21, and 32 PWR assemblies
- Surface storage times of 50 and 100 years
- Ventilation system operating times of 250 yr for SNF with 50 years of surface storage, and 200 years for 100 years of surface storage time (i.e., 300 years between removal from the reactor and start of closure operations)
- A constant ventilation thermal efficiency of 75%
- Backfill installation completed 10 years after termination of the ventilation system operation, with a mixture of 30% quartz sand and 70% bentonite

Sensitivity Study and Uncertainty Analyses Included

A number of sensitivity and uncertainty analysis studies are included in this report (Sections 3.2.2 through 3.2.7 respectively) that evaluate:

- Ventilation efficiencies of 50, 60, 70, 80, and 90%, in addition to the base case of 75%
- Ventilation system operating times of 50, 100, 150, and 200 yr, in addition to the base case of 250 yr (in combination with 50 years of surface storage)
- Drift/borehole spacing variations of 40, 50, 60, and 70 m, in addition to the base case of 30 m
- An assumed generic rock type with host rock thermal conductivities of 1, 2, 3, 4, and 5 W/m-K, and associated thermal diffusivities assuming a constant volumetric heat capacity typical of clay
- An assumed generic engineered backfill with thermal conductivity values of 1, 2, 3, 4, and 5 W/m-K. The higher values in this range are achievable using a mix of bentonite, sand, and graphite, as discussed in Appendix A, Section A.4.
- An uncertainty analysis for clay and alluvium designs, assuming the mean values of volumetric heat capacity, and with varying thermal conductivity, plus or minus one or two standard deviations, based on the Disposal Systems Evaluation Framework (DSEF) thermal properties data sheet (Greenberg et al. 2012).

Summary results for the peak rock wall and waste package surface temperatures for the base cases are presented in Section 3.2.1. The summary results of the sensitivity and uncertainty analyses are presented in Sections 3.2-2 through 3.2-7.

More detailed results are presented in Appendix B, which includes the transient plots of rock wall and waste package surface temperatures as well as plots of the contributions to the rock wall temperature from various heat sources, including adjacent waste packages and emplacement drifts/boreholes.

July 2012 Working Group Meeting and the Design Test Case for Cost Analyses

The results of these analyses were discussed in a Repository Design Concepts and Thermal Load Management (DC/TLM) team working group session hosted by LLNL on July 10 to 11, 2012, with representatives of ANL, LLNL, ORNL, SNL, and SRNL in attendance. One of the key tasks of the working group meeting was to review the open mode layout and design assumptions to facilitate the completion of the cost estimates for the various repository design alternatives. This was to support the completion of *Generic Repository ROM Cost Study* (Carter et al. 2012).

As a result of this review the DC/TLM team agreed that changes from the base case analysis assumptions were needed to accommodate larger waste packages in the open mode repository design concepts if reasonable surface storage times and ventilation duration were to be maintained.

A preliminary design test case was defined and evaluated during the meeting, with 50 years of surface storage, and 50 or 100 years of ventilation system operation for 21-UOX, 40 GWd/MT burnup waste packages in clay. On the basis of the preliminary evaluation, it was agreed that the drift/borehole spacing for the open mode repository concepts, for use in the cost analysis of Carter et al. 2012, would be increased from 30 m to 60 m spacing. The results of the design test case evaluations are presented in Section 3.3.

Temperature Constraints are a Key Factor in the Enclosed and the Open Mode Design Concepts

In the enclosed mode design concepts evaluated in FY11 (Sutton et al. 2011 and Hardin et al. 2011), the critical thermal constraints were tied to the material properties of the Engineered Barrier System (EBS), to maintain their effectiveness for long term performance assessment. Those studies assumed temperature constraints on the bentonite buffer layers of 100°C (for repository design concepts in clay and granite). These constraints limited the waste package size to less than 12 assemblies in all host environments except salt.

The open mode design concepts evaluated in this report assume a bare waste package, with or without placement of a bentonite/sand backfill mixture at closure in clay/shale and alluvium host rock designs.

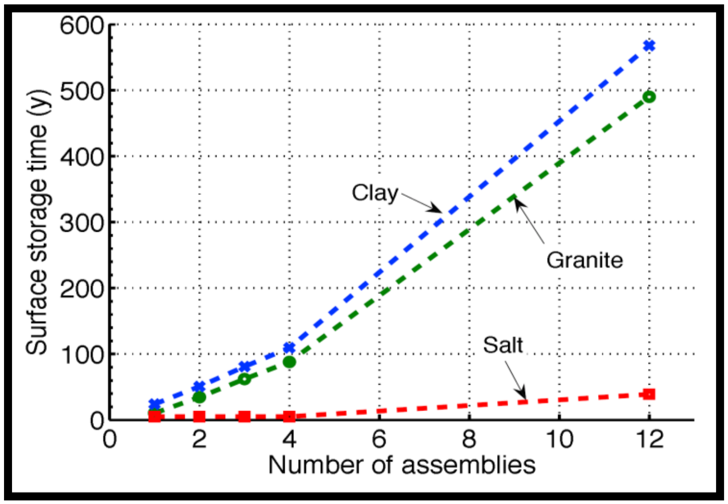
When the design test case for cost analyses was defined to accommodate larger waste packages (such as the 21 assembly UOX), the goal was to achieve host rock wall temperatures of less than or equal to a range of temperature constraint values, with the following considerations:

- A 100°C thermal limit in clay/shale (or bentonite backfill) is widely accepted to protect the desirable performance assessment properties of clay
- A 120°C thermal limit is probably defensible with more testing, and with an increased licensing risk
- A 140°C thermal limit may not be defensible, would require considerably more testing, and would entail a more difficult licensing case

Comparison of Enclosed and Open Mode Repository Design Thermal Results

Figure 1-1 compares selected results from the prior enclosed mode study (Sutton et. al 2011) with open mode results from this study. The left pane in the figure uses WP and borehole spacing of 10 and 30 m, respectively, and uses 60 GWd/MT UOX waste packages. If the temperature limit for the buffer is 100°C, a 4-PWR-assembly waste package can meet the thermal limit in clay if the waste is stored on the surface for 100 years between removal from the reactor flux and emplacement in the repository.

The right pane in the figure has the same repository layout, and has a repository closure time of 300 years. Consider the solid red curve which has the same 60 GWd/MT burnup and 50 yr surface storage time; if we wish to keep the same criteria as applied in the enclosed mode design, i.e. limit the waste package surface temperature to 100°C, the curve crosses that value at a waste package capacity of around 8-PWR-assemblies with repository closure 300 yr after the waste has been removed from the reactor flux (i.e., 50 yr of surface storage and 250 yr of ventilation at 75% efficiency in the repository after emplacement). If the temperature limit could be raised to around 130°C. A 12-PWR waste package could be accommodated in an equivalent open mode repository design.



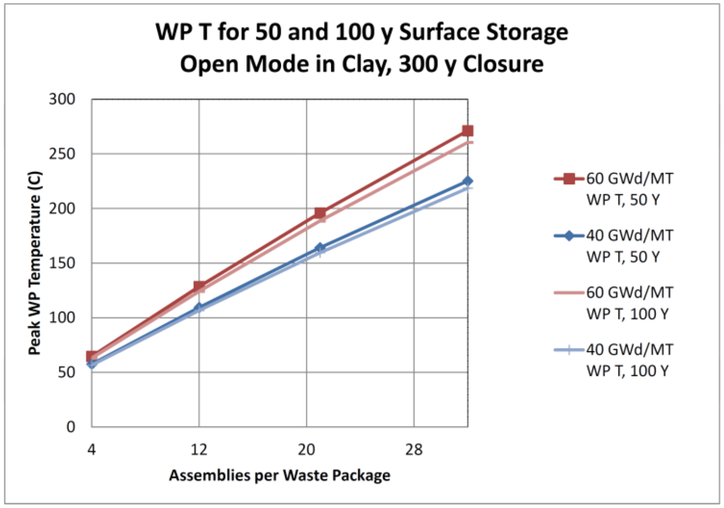


Figure 1-1 Comparison of closed mode (left) and open mode (right)

Comparing these two design points:

- The enclosed mode design requires twice the footprint of the open mode design, for the same inventory. Or, a given repository footprint can dispose of 2 times the waste if the open mode design is used. The cost savings from avoidance of multiple repositories or the avoidance of more extensive underground excavation is expected to be much larger than the cost of constructing and operating the ventilation system.
- Surface storage for the enclosed mode is twice as long (100 yr) as for the open mode (50 yr). This will reduce surface storage costs and environmental impacts if the open mode is used.
- The repository can open 50 yr earlier for the open mode, reducing the worry of hosts of surface storage facilities that they could become de facto repositories.
- The last time the waste packages are handled is at 50 yr for the open mode, which reduces risk that deterioration of the waste could make emplacement and performance assessment more difficult.
- The 250 yr ventilation period before backfilling extends the retrievability option for future generations, which could be invoked if performance confirmation shows unexpected results or if advanced fuel cycles could use the waste as feedstock.

Figure 3.2-1 shows similar figures for the rock wall temperature in clay, and for the waste package and rock wall temperatures in alluvium. If we were to change our acceptance criteria to look at the host rock wall temperature instead of the waste package temperature, then from Figure 3.2-1, applying a 100°C limit in clay would allow a 12-PWR waste package to meet the thermal constraint with 100 years of surface storage. Other changes in the repository layout and engineered backfill properties could be made to accommodate even larger waste packages with the temperature constraints applied at the host rock wall.

Thermal Results for the Design Test Case for Cost Analyses

As shown in Sections 3.3 and 4, there are sufficient design and operating parameters within our control that can be adjusted to potentially dispose of larger waste packages and meet the middle (120°C) or lower (100°C) temperature constraints, with 50 years of surface storage and 50 or 100 years of post-emplacement ventilation before closure, with or without backfill. As expected, meeting the lower temperature constraint is achieved at the expense of higher construction and operating costs.

The Design Test Case for Cost Analyses, defined in Section 3.3, used large waste packages (such as the 21 assembly UOX) and a short ventilation period (50 or 100 yr), compared to the base case and sensitivity analyses shown in Section 3.2. The initial goal of the additional analyses using the large waste package was to keep the peak temperature of the natural barriers (the host rock wall) less than or equal to a range of temperature constraint values, of 100, 120, and 140°C discussed above.

In practice, it would be possible to keep a portion of the engineered barrier of the backfill material below the temperature constraints for large waste packages and short ventilation periods if the peak wall temperature is lowered to create some margin, and the engineered backfill thermal conductivity is increased.

The tables and figures in Section 3.3 show that with 50 years of surface storage and 50 to 100 years of ventilation system operation, it is possible to keep the rock wall below some of the temperature constraints listed above, using repository layout parameters to compensate for the larger waste package and shorter ventilation time compared to the base case design used in Section 3.2.

As expected, meeting lower temperature constraints is achieved at the expense of higher construction and operating costs. For each geologic medium, the following design and operating parameters can be adjusted in the open mode repository designs to meet the thermal constraints:

- Ventilation system design (thermal efficiency)
- Duration of preclosure operations and ventilation
- Drift or borehole spacing
- Waste package spacing
- Engineered backfill thermal conductivity

In clay/shale, Figure 3.3-1 and Table 3.3-1 show that we can meet the 120°C wall temperature constraint with the repository layout described in Hardin et al. 2012c (10 m WP spacing and 60 m borehole spacing) with 50 years of ventilation, and come close to the 100°C constraint with 100 years of ventilation.

If we are willing (based on repository performance assessment calculations) to have a sacrificial core of clay around the emplacement drift that exceeds the temperature constraint, and apply the temperature constraint at 3 m into the host rock, the 100°C constraint is only slightly exceeded at that depth with 50 years of ventilation, and is met with a small margin with 100 years of ventilation, as shown in Figure 3.3-1 and Table 3.3-1.

Figure 3.3-2 shows that if we are willing to increase the repository footprint and cost by changing the waste package spacing from 10 m to 15 m, then the 100°C temperature constraint at the wall can be met with 50 years of ventilation.

2. INTRODUCTION

2.1 ENCLOSED AND OPEN REPOSITORY DESIGN CONCEPTS AND OPERATING MODES

The FY11 disposal concepts report: *Generic Repository Design Concepts and Thermal Analysis* (Hardin et al. 2011), recognized open and enclosed emplacement modes, and recommended further work to evaluate one or more open modes (Hardin et al. 2011, Section 6). Enclosed modes were defined to include disposal concepts that call for waste packages to be in direct contact with any surrounding solid medium such as buffer material, backfill, or host geology. For enclosed modes, the direct contact begins immediately at emplacement or shortly thereafter, with that contact influencing peak near-field temperature. Open modes maintain unsaturated, air-filled open spaces around the waste packages for some time prior to permanent closure, and even after closure for some concepts.

Open modes for clay and alluvium are evaluated in this report. Sandia National Laboratories performed a preliminary assessment of a hybrid open mode concept in salt. Here, “hybrid” indicates separate ventilation tunnels between emplacement alcoves. The SNL assessment used finite element analysis codes, and therefore the analysis for the salt repository design concept is not evaluated here.

2.2 OPEN MODE REPOSITORY DESIGN CONCEPTS IN CLAY AND ALLUVIUM

The open mode design concepts are outlined in *Open Emplacement Modes Analysis and Selection* (Hardin et al. 2012a) in Sections 3.1 for clay/shale, and 3.2 for alluvium respectively.

Note that the open mode design concepts in *Design Concepts/Thermal Load Management Summary,* (Hardin et al. 2012c) evolved based on the analysis results in this report. The updated designs in Hardin et al. 2012c include emplacement drift spacing of 60 m center-to-center, to accommodate the thermal loading from larger waste packages, compared to the 30 m drift spacing used for the base cases in this report.

Figures 2.2-1 and 2.2-2 depict the repository conceptual designs for clay and alluvium respectively.

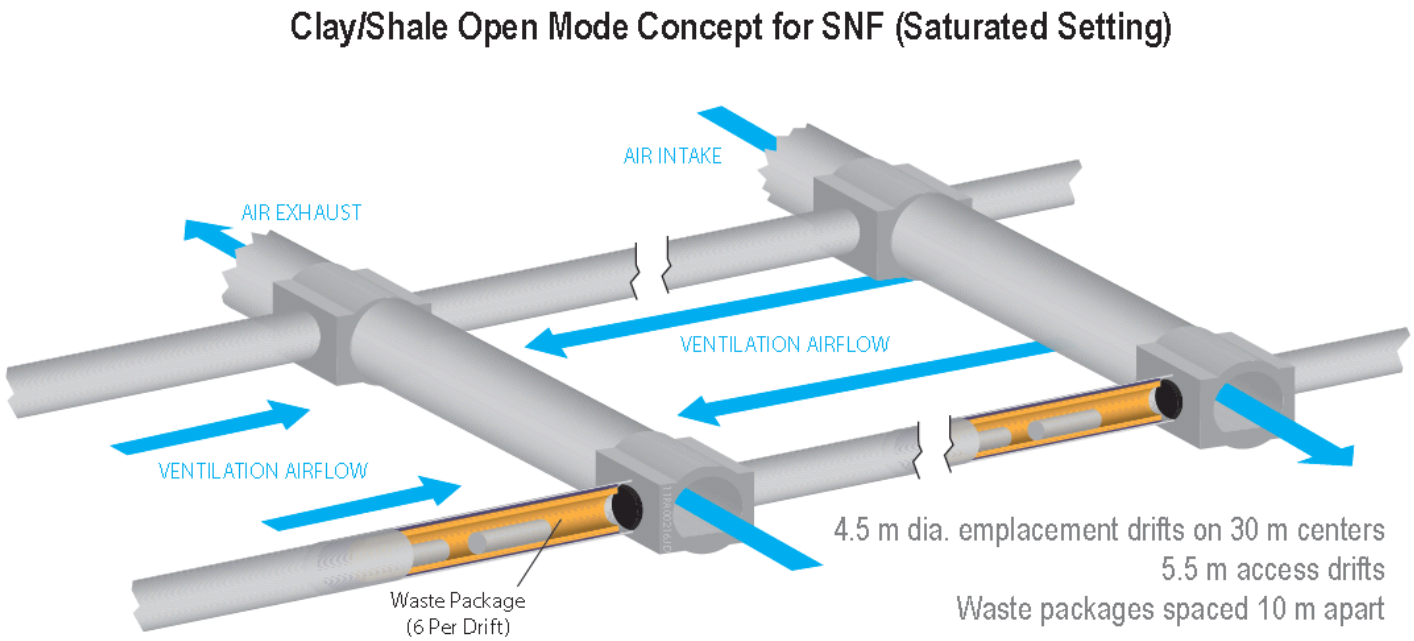


Figure 2.2-1 Clay / Shale Open Mode Design Concept (Saturated Setting)

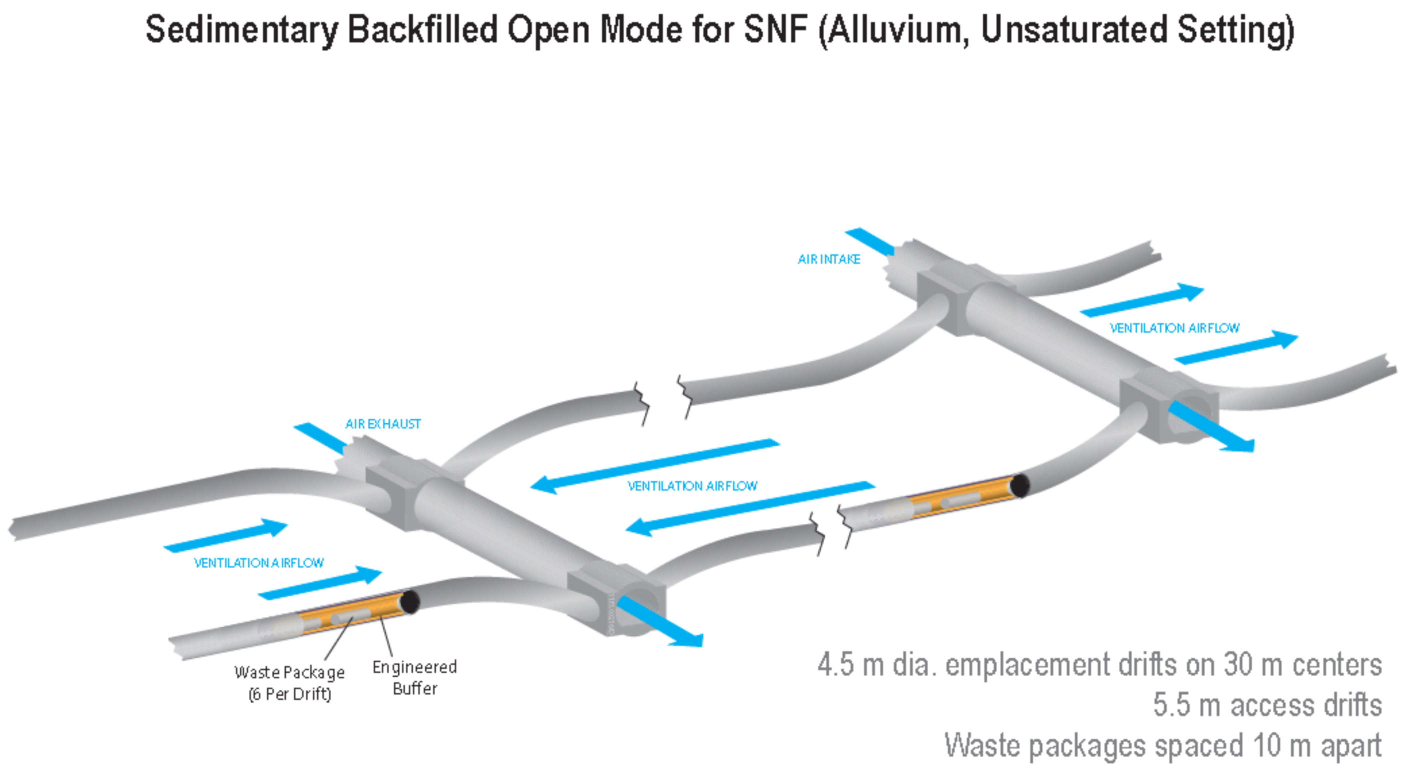


Figure 2.2-2 Alluvium Open Mode Concept (Unsaturated Setting)

2.3 Open Mode Design Operating Assumptions

This report assumes that used nuclear fuel is emplaced in the repository at 50 or 100 years out of reactor, and then subsurface operations continue with forced ventilation for 250 or 200 years, such that closure commences when the fuel is 300 years out of reactor. At closure, it is assumed that the ventilation heat removal stops, and backfilling operations commence.

It is assumed that backfilling will take approximately 10 years to complete. In the analysis from 300 to 310 years the air gap is assumed to continue to exist in the open emplacement drifts, with radiation heat transfer to the walls, but with no heat removal by forced ventilation. Backfilled conditions are assumed to commence at 310 years, as a step function.

All of the base cases for clay/shale and alluvium repository concepts assume backfilling of the emplacement drifts at closure. However, the current open mode design concepts, discussed in Hardin et al. 2012c, assume that in the alluvium repository design case; only the access mains are backfilled and the emplacement drifts remain open. The host rock temperature transient calculation is essentially the same with or without backfill in the emplacement drifts, since it is based on the decay heat source terms, assuming a continuous rock media within the emplacement drifts up to the heat source. The volumetric heat capacity of the host rock is comparable to or greater than the volumetric heat capacity of the backfill, so that the calculated temperature transient at the drift wall should be similar with or without the backfill present.

However, after the addition of backfill, the waste package surface temperature rises until the temperature gradient is sufficient to drive the decay heat through the backfill layer.

The design test case evaluated for costing in Section 3.3 evaluated a range of waste package temperatures with and without backfill, having thermal conductivity values for three backfill compositions: 0.6 W/m-K for dry bentonite, 1.2 W/m-K for a 70% bentonite, 30% sand mixture, and 2.0 W/m-K for a possible mixture of bentonite, sand, and graphite. The design test case was run for clay, but the nature of the response is applicable to alluvium as well.

In the case with no backfill of the emplacement drifts at closure, a future drift collapse could be considered to be bounded by the effect of adding backfill to the emplacement drift at the time of drift collapse. The effects of drift collapse, at the time it occurs, can be estimated by comparing the waste package temperature curves for the backfilled and un-backfilled cases.

If there are significant void spaces in the rubble due to drift collapse, the resulting waste package temperature will be between the temperatures calculated assuming a compacted backfill, and the case with no backfill.

The specific details of the ventilation system design and operations are not addressed, but the methodology for achieving a given ventilation system thermal efficiency, or heat removal level, is straightforward. Future open mode analysis will address ventilation system design if necessary. For the current analysis, a constant ventilation system thermal efficiency for heat removal is assumed (see Appendix A, Section A.2). This directly affects the net heat going into the host rock and thus the transient rock temperature. When the ventilation system is turned off, 100% of the heat generation goes into the rock.

3. Modeling and Analysis

3.1 Conceptual Model

3.1.1 Geometry

Figure 3.1-1 shows a generic EBS, with standard names adopted for this report, to describe the various components. These names may be somewhat different from those published from design to design.

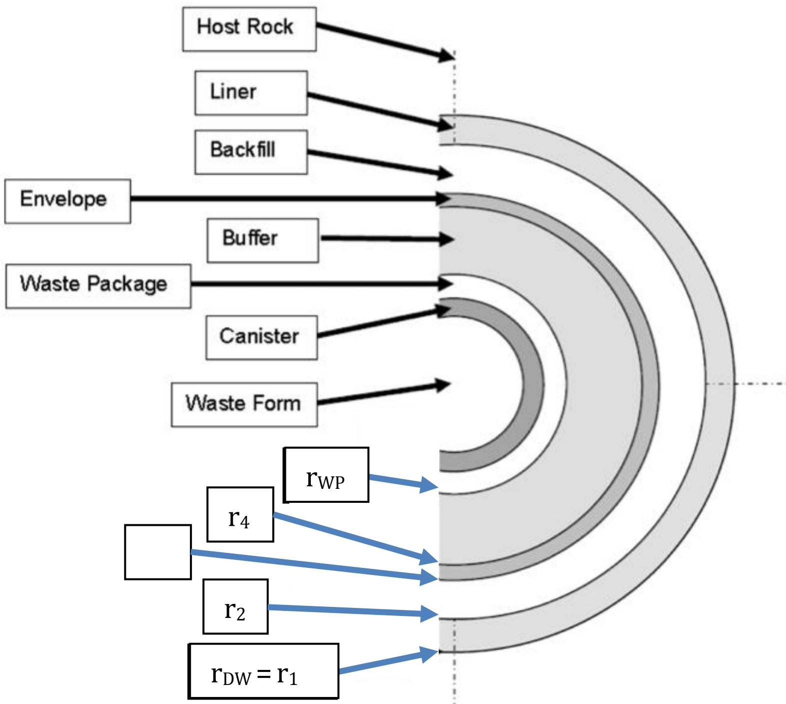


Figure 3.1-1 Illustration defining the terminology used for the potential layers of the near-field Engineered Barriers System (EBS) from host rock to waste form

In the open mode design concepts evaluated in this report, the buffer, envelope, and backfill layers are all replaced with an air gap to allow operation of a ventilation system prior to closure. At closure, the air gap becomes one continuous backfill layer, with 10 years of no ventilation during backfill installation.

In Figure 3.1-1, the numbered radii represent the outer radius of the various engineered barrier layers r_1, r_2, r_3, and r_4 for the liner, backfill, envelope, and buffer layers respectively. In the open mode designs, the air gap, and subsequently the backfill, occupy the region bounded by r_2 and r_{WP}.

Table 3.1-1 and Figure 3.1-2 describe the repository base case layout in terms of axial (waste package center-to-center spacing) and lateral (drift / borehole center-to-center spacing) assumed for both clay and alluvium environments. Spacing is center to center, as opposed to the gap between items that is sometimes used.

Several drift spacing sensitivity studies also evaluated lateral (i.e., borehole) spacing of 40, 50, 60, and 70 m in addition to the base case of 30 m (see Section 3.2.4).

Table 3.1-1 Open Mode Design Concept Repository base case layout axial

Geology	SNF Waste Packages	
	Axial	Lateral
Clay	10	30
Alluvium	10	30

In the enclosed mode repository design concepts, the components and dimensions of the EBS are tailored to each geologic medium. However, for the open mode analysis, where we are assuming a bare waste package inside a drift, with a rock wall opening diameter of 4.5 m and a steel liner, the dimensions are essentially fixed. The only parameter that is varied is the thickness of the air gap between the outside of the waste package and the inside of the liner required to keep the host rock opening at 2.25 m radius, as the size of the waste package changes to accommodate the changing waste package capacities (4, 12, 21, and 32 assemblies). The dimensions are summarized in Table 3.1-2. This table is based on Table 3 of Hardin et al. 2012a.

Table 3.1-2 Waste package diameter versus waste package capacity

Waste Package	Diameter, m
4 PWR assemblies	0.82
12 PWR assemblies	1.29
21 PWR assemblies	1.60
32 PWR assemblies	2.00

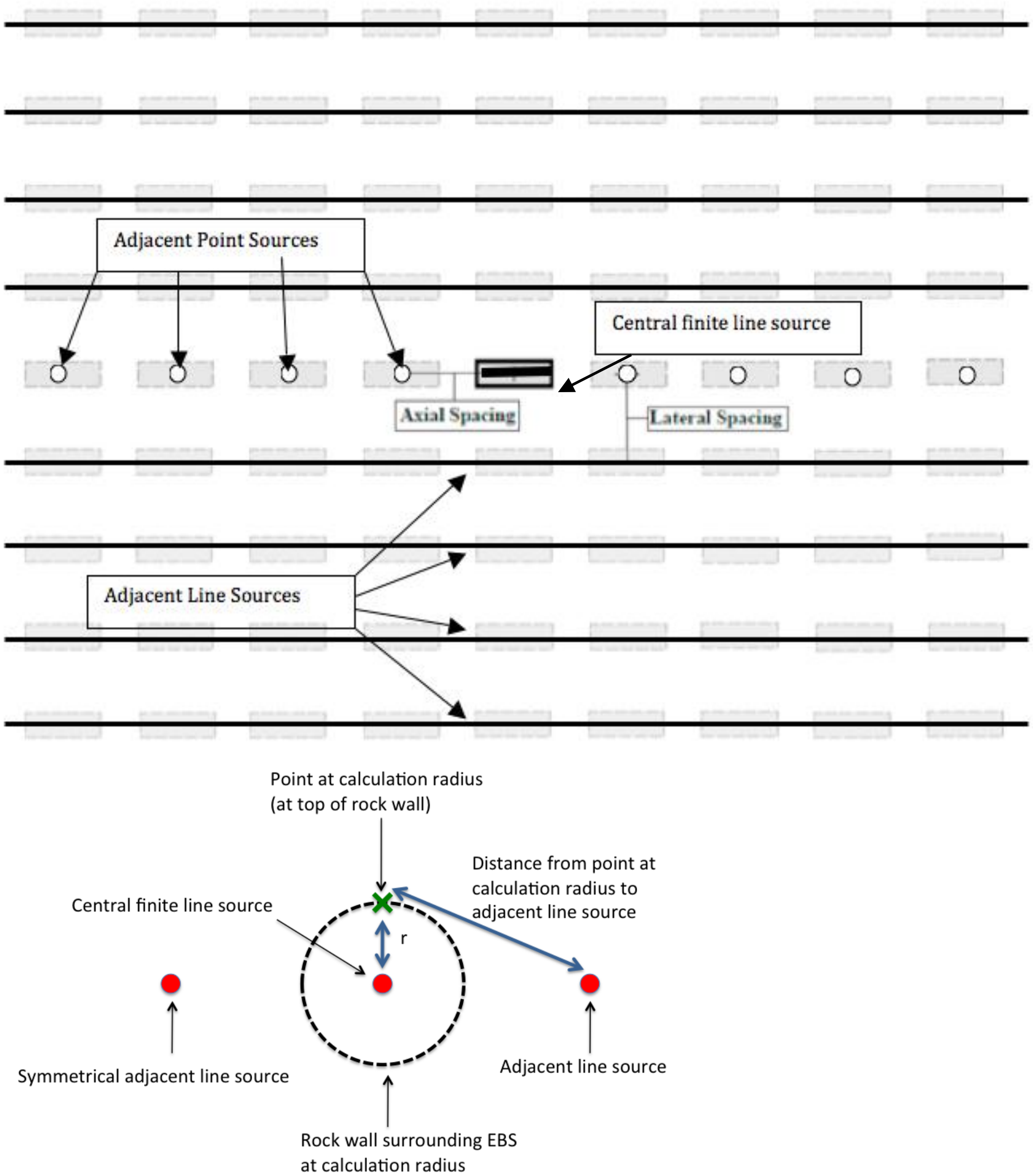


Figure 3.1-2 Conceptual layout of a central waste package of interest and both axial and lateral emplacement lines (plan and elevation view)

3.1.2 Approach

The methodology and approach are the same as in Sutton et al. 2011; however, a simplified design was analyzed for the open mode cases. For the current analysis, there is no detailed EBS configuration, only a bare waste package and a steel liner inside the drifts/boreholes in clay and alluvium.

The waste package surface temperature transients can be considered as a bounding temperature for the surface of any other installed EBS components. For example, if a "Supercontainer" consisting of a waste package and a buffer layer contained inside a steel envelope were emplaced instead of a bare waste package, the outside temperature of the envelope should be less than the calculated bare waste package temperature. Also, after backfill is added, the thermal gradient within the backfill would envelope the EBS gradient as long as the thermal conductivities of the EBS components are higher than that of the backfill.

Other changes to the approach were made to incorporate radiation heat transfer across the air gap, ventilation thermal efficiency and duration of ventilation, and the closure and backfilling operations.

The base case analyses all assumed a total time to closure of 300 years, with backfill operations complete in another 10 years after that. The 300-year closure time is the sum of the surface storage period and the ventilation period, such that 50 years of surface storage is associated with 250 years of ventilation, and 100 years of surface storage is associated with 200 years of ventilation.

3.1.3 Input Data and Assumptions

The decay heat curve for a single assembly of UOX SNF with burnup of 40 or 60 GWd/MT is shown in Figure 3.1-3, and is also provided in Table 3.1-3. Note that there is a significant difference between the decay heat values for surface storage times of 50 or 100 years, which results in significant differences in rock wall and waste package surface temperatures for enclosed mode repository design concepts. That is because, in the enclosed mode repository designs, the temperatures peak shortly after emplacement. However, for the open mode repository designs, at least 75% of that decay heat is removed by the ventilation system, and the peak temperatures don't occur until after the ventilation system is turned off (at 300 years out of reactor for the base case analyses). As a result, the difference in peak rock wall and waste package surface temperatures between the 40 and 60 GWd/MT cases is not as significant for the open mode designs as it is for the enclosed mode repository designs.

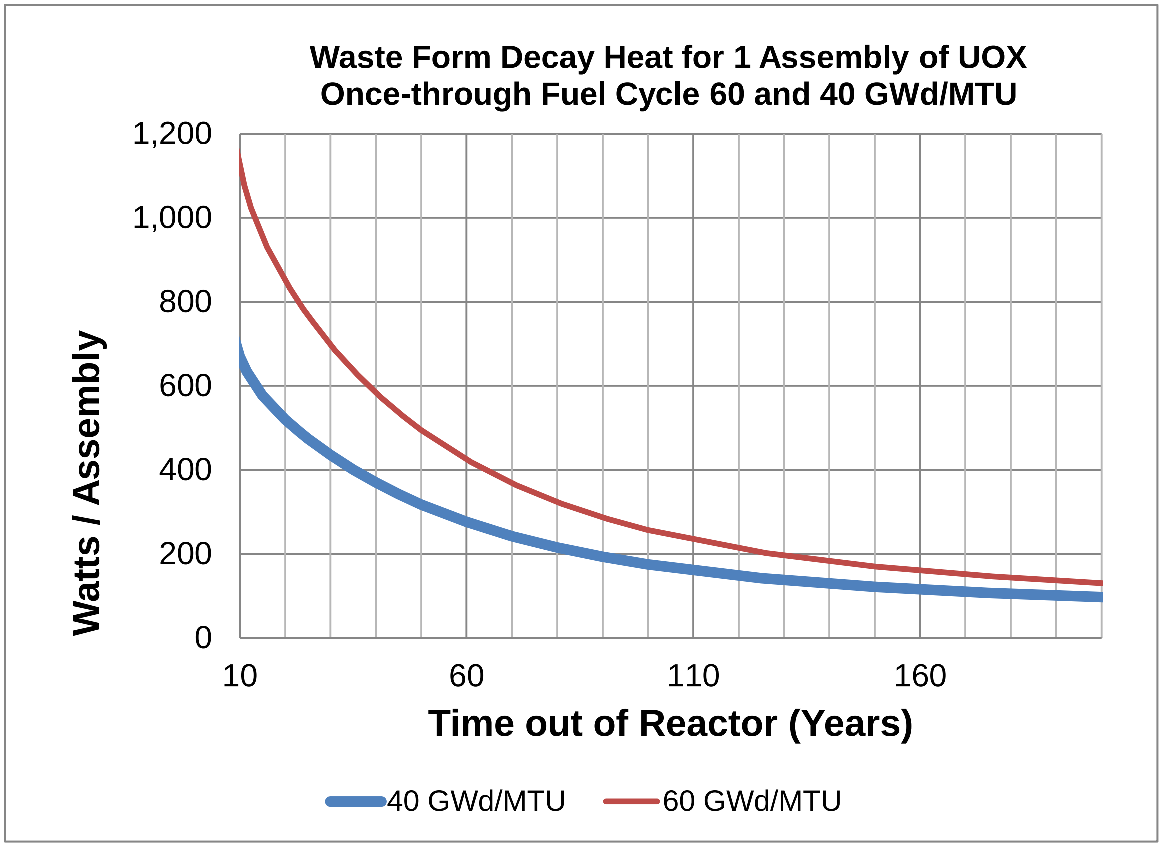


Figure 3.1-3 Decay heat curves for one UOX assembly

Table 3.1-3 Decay heat data per assembly and per MT for 40 and 60 GWd/MT burnup UOX (PWR SNF)

	Decay Heat per Assembly		Decay Heat per MT*	
Time out of Reactor (yrs)	40 GWd/MT PWR SNF	60 GWd/MT PWR SNF	40 GWd/MT PWR SNF	60 GWd/MT PWR SNF
5	1,028.2	1,696.0	2,187.6	3,608.5
5.1	1,010.6	1,670.0	2,150.2	3,553.2
5.5	949.1	1,578.0	2,019.4	3,357.4
5.75	916.7	1,529.0	1,950.4	3,253.2
6	888.0	1,484.0	1,889.3	3,157.4
8	742.9	1,249.0	1,580.7	2,657.4
10	670.0	1,122.0	1,425.6	2,387.2
11.5	634.2	1,058.0	1,349.4	2,251.1
15	576.9	953.3	1,227.5	2,028.3
20	520.0	849.9	1,106.4	1,808.3
23	491.8	799.0	1,046.4	1,700.0
25	474.4	767.9	1,009.5	1,633.8
30	435.1	698.0	925.7	1,485.1
35	400.4	637.1	851.9	1,355.5
40	369.6	583.6	786.4	1,241.7
45	342.1	536.4	728.0	1,141.3
50	317.6	494.5	675.7	1,052.1
60	275.9	424.2	587.0	902.6
70	242.3	368.2	515.5	783.4
80	215.0	323.2	457.5	687.7
90	192.9	286.8	410.4	610.2
100	174.7	257.2	371.8	547.2
125	142.1	203.9	302.4	433.8
150	121.3	169.7	258.1	361.1
175	107.4	146.8	228.4	312.3
200	97.5	130.4	207.4	277.4
225	90.1	118.3	191.7	251.7
250	84.3	108.8	179.3	231.5
300	75.4	94.8	160.4	201.6
350	68.7	84.7	146.2	180.1
400	63.3	76.9	134.6	163.6
450	58.7	70.7	124.8	150.4
500	54.7	65.6	116.3	139.5
600	48.0	57.5	102.2	122.2

Table 3.2-3 Continued	Decay Heat per Assembly		Decay Heat per MT*	
Time out of Reactor (yrs)	40 GWd/MT PWR SNF	60 GWd/MT PWR SNF	40 GWd/MT PWR SNF	60 GWd/MT PWR SNF
700	42.7	51.2	90.8	109.0
800	38.2	46.2	81.3	98.4
900	34.5	42.1	73.4	89.6
1000	31.3	38.6	66.6	82.2
1250	25.3	32.1	53.8	68.2
1500	21.2	27.6	45.1	58.6
1750	18.4	24.4	39.1	52.0
2000	16.4	22.2	34.9	47.3
2250	15.0	20.6	32.0	43.9
2500	14.0	19.5	29.9	41.4
3000	12.7	17.9	27.1	38.0
4000	11.4	16.0	24.2	34.1
5000	10.5	14.8	22.4	31.5
6000	9.8	13.8	20.9	29.3
7000	9.2	12.8	19.6	27.3
8000	8.7	12.0	18.4	25.4
9000	8.1	11.2	17.3	23.8
10000	7.7	10.5	16.3	22.3
20000	4.6	5.9	9.7	12.6
50000	1.7	2.1	3.5	4.4
100000	0.6	0.8	1.3	1.8
200000	0.4	0.5	0.8	1.2
500000	0.3	0.4	0.6	0.9
1000000	0.2	0.3	0.5	0.6

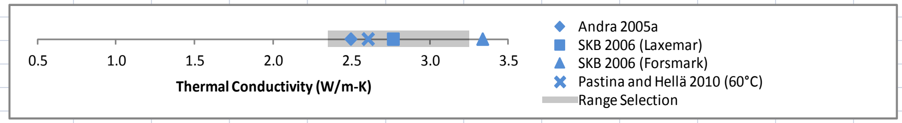
*This assumes 0.47 MT per UOX assembly (based on a 17x17 PWR fuel rod configuration).

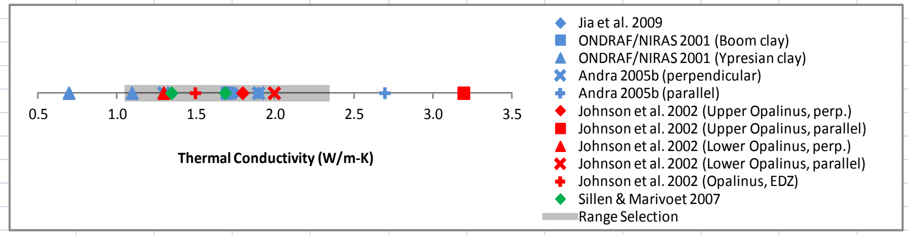
Figure 3.1-4 provides uncertainty analysis data for clay and alluvium thermal properties, derived from the Disposal Systems Evaluation Framework (DSEF) MATERIALS-THERMAL PROPERTIES worksheet, and presented in Tables 1 and 2 of the draft report: *Parameter Uncertainty for Thermal Analysis* (Hardin et al. 2012b).

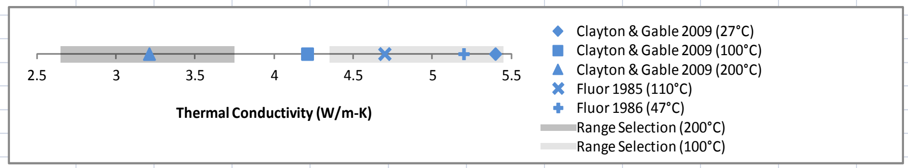
Host Rock Thermal Conductivity

Low	High	Source	Average	Std. Dev.
Granite				
2.50		Andra 2005a	2.81	0.37
2.77		SKB 2006 (Laxemar)		
3.34		SKB 2006 (Forsmark)		
2.61		Pastina and Hellä 2010 (60°C)		
2.4	3.2	Range Selection		
Clay/Shale				
1.75		Jia et al. 2009	1.73	0.61
1.70		ONDRAF/NIRAS 2001 (Boom clay)		
0.70	1.1	ONDRAF/NIRAS 2001 (Ypresian clay)		
1.3	1.9	Andra 2005b (perpendicular)		
1.9	2.7	Andra 2005b (parallel)		
1.8		Johnson et al. 2002 (Upper Opalinus, perp.)		
3.2		Johnson et al. 2002 (Upper Opalinus, parallel)		
1.3		Johnson et al. 2002 (Lower Opalinus, perp.)		
2.0		Johnson et al. 2002 (Lower Opalinus, parallel)		
1.5		Johnson et al. 2002 (Opalinus, EDZ)		
1.35	1.69	Sillen & Marivoet 2007		
1.1	2.3	Range Selection		
Salt				
5.4		Clayton & Gable 2009 (27°C)	4.88	0.53
4.2		Clayton & Gable 2009 (100°C)		
4.7		Fluor 1985 (110°C)		
5.2		Fluor 1986 (47°C)		
3.2		Clayton & Gable 2009 (200°C)	3.21	0.53
4.4	5.4	Range Selection (100°C)		
2.7	3.7	Range Selection (200°C)		
Alluvium				
1.05		Wollenberg et al. 1982 (in situ)	1.06	0.11
0.91	1.14	Wollenberg et al. 1983 (downhole probe)		
1.0	1.2	Smyth et al. 1979 (unsat., consolidated)		
1.0	1.2	Range Selection (unsat., consolidated)		
0.98	1.42	Wollenberg et al. 1982 (wet, consolidated)	1.49	0.34
1.21	1.81	Wollenberg et al. 1982 (wet, consolidated)		
1.51	2	Wollenberg et al. 1982 (wet, consolidated)		
1.5		Wollenberg et al. 1982 (saturated, consolidated)		
1.2	1.8	Range Selection (saturated, consolidated)		
Crystalline Basement				
3.0		Brady et al. 2009		

No temperature limits identified for deep borehole disposal concept (Hardin et al. 2011).







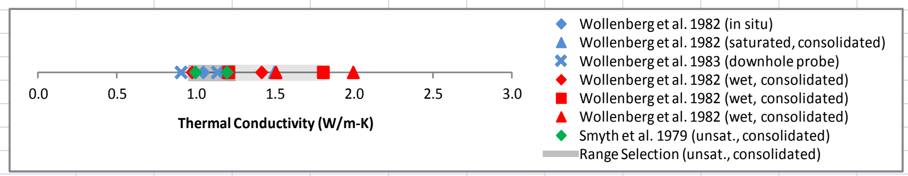


Figure 3.1-4 Host Rock Thermal Conductivity Ranges and Parameter Variance

3.2 Summary of Host Rock and Waste Package Temperature Results

This section includes summary tables presenting the rock wall and waste package peak temperatures for the various cases analyzed. Appendix B contains the full set of results for all of the base cases, as well as for the sensitivity studies and uncertainty analyses. Appendix B includes tabular results in addition to transient temperature plots for rock wall and waste package surface temperatures. Tables in each Appendix section identify the case numbers and associated figure numbers.

The following sections present summary tables of the peak temperature data, and graphical summaries of the peak data and the sensitivity studies performed.

- Section 3.2.1 provides a summary of the base case thermal analysis results.
- Section 3.2.2 presents a sensitivity analysis to ventilation thermal efficiency including 50, 60, 70, 80, and 90% in addition to the base case of 75%. See also Appendix B.3.1.
- Section 3.2.3 presents sensitivity to ventilation system operating time after emplacement 250, 200, 150, 100, and 50 yrs, assuming 21-UOX, 40 GWd/MT, Veff=90%, 10 yr to backfill, and a clay repository. See also Appendix B.3.2. All the cases assume 50 years of surface storage.
- Section 3.2.4 presents sensitivity to drift spacing of 30, 40, 50, 60, and 70 m, for a clay repository with cases for 21 and 32-UOX WPs, 40 GWd/MT, 50 yr of storage, ventilation for 250 yr at 90% efficiency, and 10 years to backfill. See also Appendix B.3.3.
- Section 3.2.5 presents sensitivity to host rock thermal conductivity, assuming a generic host rock with 1, 2, 3, 4, and 5 W/m-K and a volumetric heat capacity typical of clay. All cases used a 21-UOX WP with 40 and 60 GWd/MT burnup, 50 yr of storage, 250 yr of ventilation, and 10 yr of backfill emplacement. See also Appendix B.3.4.
- Section 3.2.6 presents sensitivity to backfill thermal conductivity, assuming a generic engineered backfill (material mixture undefined) with 1, 2, 3, 4, and 5 W/m-K. All cases used a 21-UOX WP with 50 yr of storage, 250 yr of ventilation, and 10 yr of backfill emplacement. See also Appendix B.3.5.
- Section 3.2.7 presents uncertainty analysis for host rock thermal conductivity in clay and alluvium, assuming a mean value plus or minus 1 and 2 standard deviations. See also Appendix B.4.

3.2.1 BASE CASE THERMAL ANALYSIS RESULTS SUMMARY

Figure 3.2-1 presents a summary of peak host rock wall and waste package temperatures for 50 and 100 yr surface storage times. Table 3.2-1 is a summary of the base case peak temperature results for the open mode in clay and alluvium, for burnups of 40 and 60 GWd/MT. The transient plots for the base cases are given in Appendix B.2, and Table 3.2-1 identifies the associated figure numbers for each case. All cases in this table assume 75% ventilation efficiency, with ventilation duration plus surface storage time = 300 years. Backfill emplacement starts at 300 years with a 30% sand, 70% bentonite mixture, and backfilling operations are completed in 10 years. Heat transfer from the surface of the waste package to the drift/borehole liner switches from radiation to conduction through the backfill at 310 years.

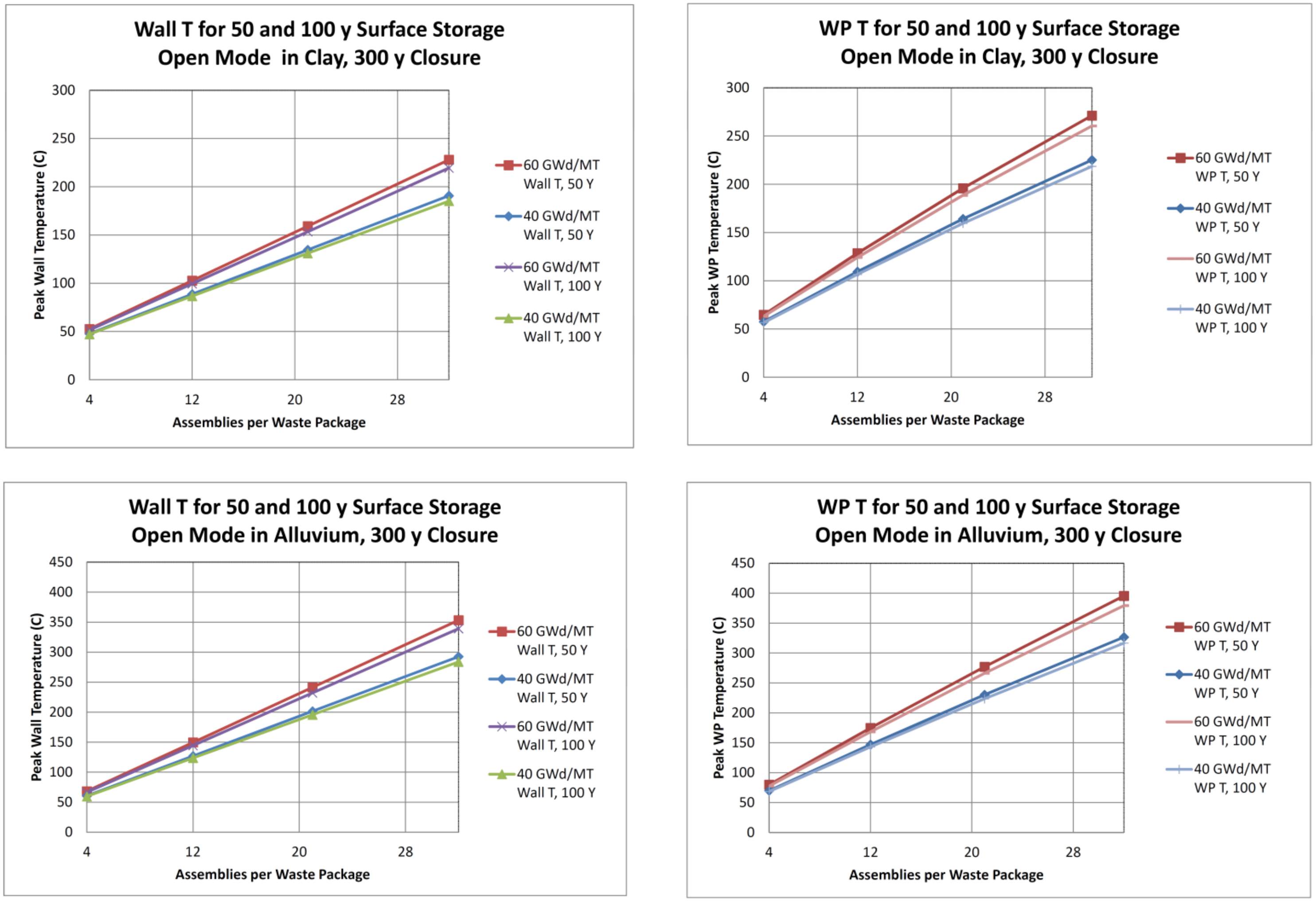


Figure 3.2-1 Peak wall and waste package (WP) temperatures for 50 and 100 yr surface storage for open mode emplacement in clay and alluvium, with closure at 300 yr, and with 40 and 60 GWd/MT burnup

Table 3.2-1 Summary of base case analyses - peak rock wall and waste package temperatures for 40 and 60 GWd/MT cases, with 50 and 100 years of surface storage

Disposal Scenarios		Surface Storage = 50 yr						Surface Storage = 100 yr					
Geology	**SNF / Burnup (GWd/MT)**	**Figure Number**	**Case Number**	**Peak Rock Temp, °C**	**Peak Time, yr**	**WP Surface Temp, °C**	**Peak Time, yr**	**Figure Number**	**Case Number**	**Peak Rock Temp, °C**	**Peak Time, yr**	**WP Surface Temp, °C**	**Peak Time, yr**
Clay	4-UOX 40	B.2-1	13	47.8	593	64.8	383	B.2-2	14	47.1	624	63.7	401
	4-UOX 60	B.2-3	15	52.6	567	71.3	367	B.2-4	16	51.5	628	69.5	382
	12-U0X 40	B.2-5	17	88.3	593	102.5	488	B.2-6	18	86.3	628	100	536
	12-UOX 60	B.2-7	19	102.6	103	102.6	103	B.2-8	20	99.3	598	124.2	470
	21-UOX 40	B.2-9	21	133.9	593	158.7	488	B.2-10	22	131	624	159.5	515
	21-UOX 60	B.2-11	23	159.1	567	195.8	468	B.2-12	24	153.4	628	188.6	496
	32-UOX 40	B.2-13	25	189.7	593	218.8	522	B.2-14	26	184.2	628	212.4	544
	32-UOX 60	B.2-15	27	228	567	271.2	487	B.2-16	28	219.4	628	260.5	496
Alluvium	4-UOX 40	B.2-17	41	60.6	593	64.9	533	B.2-18	42	59.5	628	63.6	577
	4-UOX 60	B.2-19	43	68.2	567	73.5	515	B.2-20	44	66.5	628	71.5	536
	12-U0X 40	B.2-21	45	126.9	593	139.6	541	B.2-22	46	123.6	628	135.9	577
	12-UOX 60	B.2-23	47	149.6	567	165.5	515	B.2-24	48	144.4	628	159.4	536
	21-UOX 40	B.2-25	49	201.5	593	223.7	541	B.2-26	50	195.7	628	217.2	577
	21-UOX 60	B.2-27	51	241.2	567	269	515	B.2-28	52	232.1	628	258.4	536
	32-UOX 40	B.2-29	53	292.6	593	326.5	541	B.2-30	54	283.8	628	316.6	577
	32-UOX 60	B.2-31	55	353.2	567	395.5	515	B.2-32	56	339.2	628	379.3	536

Waste package temperatures are incrementally hotter than the rock wall. Clay temperatures are lower than alluvium due to the lower thermal conductivity of alluvium. The effect of storage time is minimal because the conceptual model replaces reduced storage time with additional ventilation time (removing 75% of the heat in that period). Burnup is a significant factor, particularly for large WPs.

3.2.2 Sensitivity to Ventilation System Thermal Efficiency

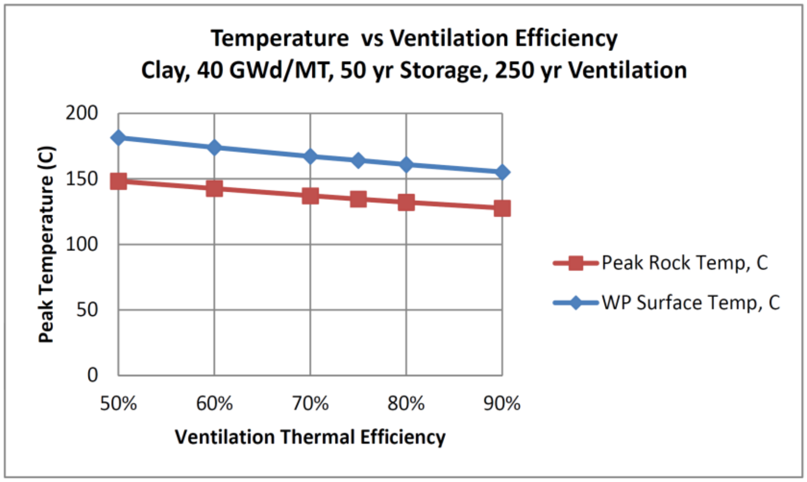
Table 3.2-2 presents sensitivity to ventilation thermal efficiency assuming 21-UOX WPs, 40 GWd/MT, 50 yr storage, 300 yr total operation, and 10 yr to backfill, for a clay repository. Axial spacing is 10 m, and lateral (drift/borehole) spacing is 30 m. Transient temperature plots for these cases are presented in Appendix B.3.1.

Table 3.2-2 List of cases used in the ventilation efficiency sensitivity study for clay

Figure Number	Case Number	Ventilation Thermal Efficiency		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-1	21a	50%		148.2	491		181.5	410
B.3-2	21b	60%		142.7	545		174.0	442
B.3-3	21c	70%		137.1	567		167.2	468
B.3-4	**21**	**75%**		134.6	593		164.1	488
B.3-5	21d	80%		132.2	608		161.0	516
B.3-6	**21e**	**90%**		127.6	659		155.2	539

The base case (21) has 75% ventilation efficiency. Case 21 is also used in Appendix B.2. Case 21e is the base case for the sensitivity study in Appendix B.3.2.

Figure 3.2-2 summarizes the results for the ventilation efficiency sensitivity cases. Ventilation efficiency has enough of an effect on temperature that it should be included in cost/performance trade studies. The top pane shows the effect of ventilation thermal efficiency on peak wall and WP temperatures for one repository design. The bottom pane shows the transient rock wall and WP temperatures for six ventilation thermal efficiencies. The peak temperature from each curve is a data point on the red curve of the top plot.



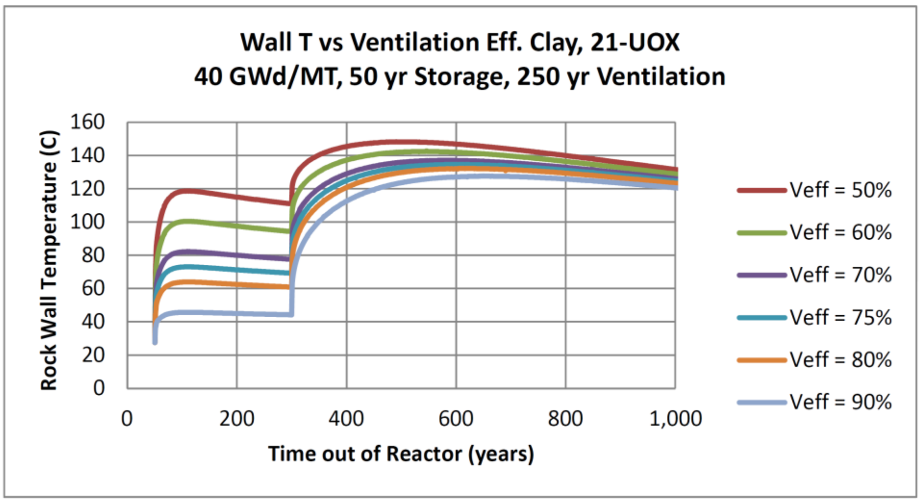


Figure 3.2-2 Effect of ventilation thermal efficiency on peak wall and WP temperatures for one repository design

3.2.3 Sensitivity to Ventilation System Operating Time

A ventilation efficiency of 90% is used in a clay repository with 21-UOX WPs that have 40 GWd/MT burnup. Storage time is 50 yr before the start of ventilation. Axial spacing is 10 m, and lateral (drift/borehole) spacing is 30 m, except for the last two cases. The last three cases explore how higher temperatures due to shorter ventilation can be compensated for by wider drift or borehole spacing.

Table 3.2-3 and Figure 3.2-3 show the results of the cases analyzed. There are diminishing returns on ventilation duration at long ventilation times. The top panel of the figure shows the effect of ventilation duration on peak wall and waste package temperatures for one repository design and very high ventilation efficiency (90%). The bottom panels show the transient rock wall temperatures for five ventilation durations. The peaks of the transient curves on the lower left figure are the data points for the red curve in the top figure. The lower right figure shows details around the time of closure, with the initial steep rise beginning to level during the 10 year period between ventilation cessation and backfill installation, and then the curves rise again steeply when the insulating backfill replaces the more efficient radiation heat transfer.

Table 3.2-3 Sensitivity to ventilation system operating time after emplacement including 250, 200, 150, 100, and 50 yrs

Figure Number	Case Number	Ventilation Period, yr	Drift Spacing, m		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-7	21e	250	30		127.6	659		155.2	539
B.3-8	21f	200	30		134.3	602		164.3	479
B.3-9	21g	150	30		142.0	518		175.3	417
B.3-10	21h	100	30		152.0	424		190.1	314
B.3-11	21i	50	30		167.4	322		221.4	139
B.3-12	21j	50	40		141.3	349		207.5	118
B.3-13	21k	50	50		124.2	322		203.3	111

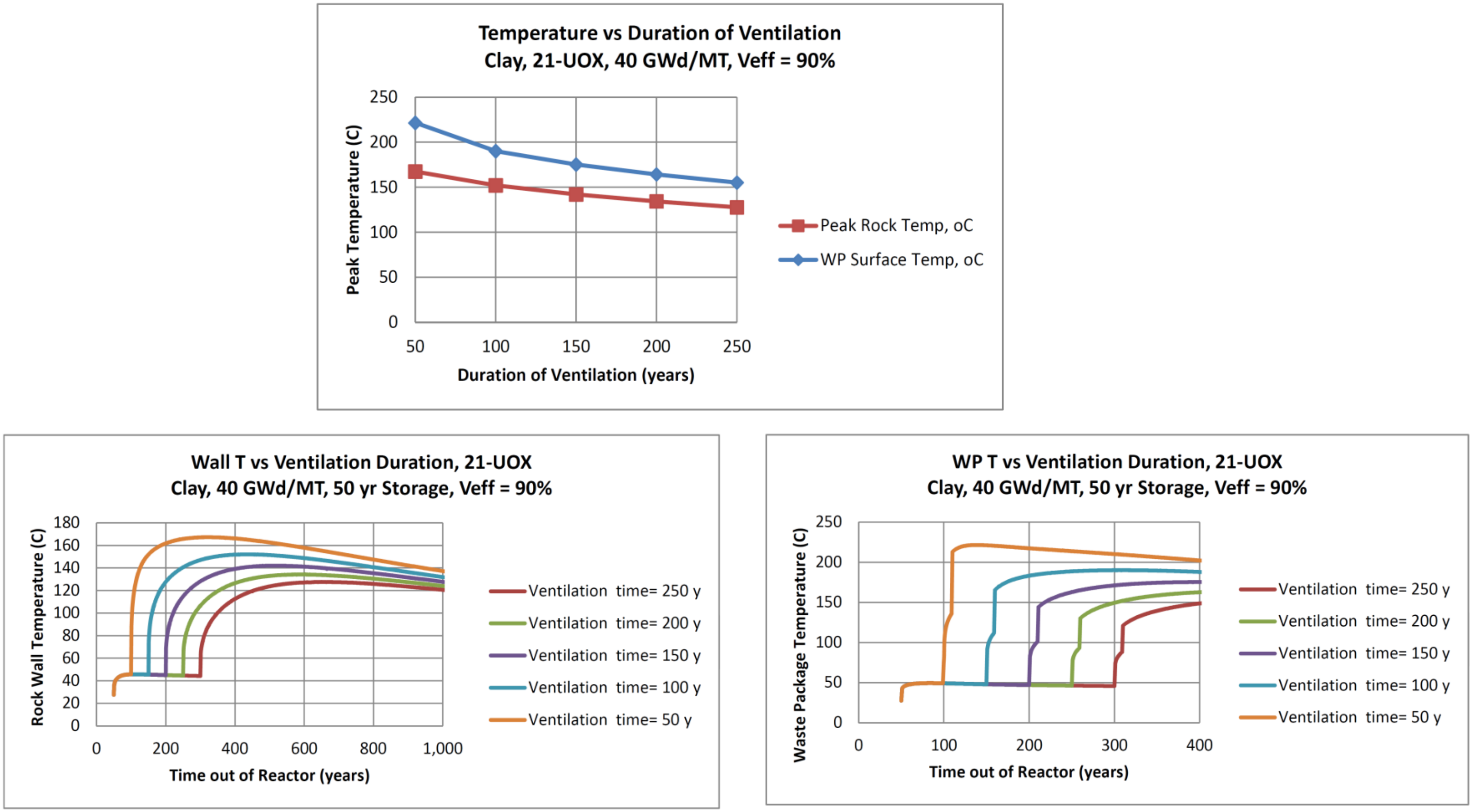


Figure 3.2-3Effect of ventilation duration on peak wall and waste package temperatures for one repository design at high ventilation efficiency

3.2.4 Sensitivity to Emplacement Drift Spacing

Table 3.2-4 and Figure 3.2-4 summarize the peak temperatures and times for the drift/borehole spacing. The top panes of the figure present these results graphically, and the lower panes show the transient temperature results.

This section assumes 40 GWd/MT burnup, and storage, ventilation, and backfill installation times of 50, 250, and 10 yr, respectively. Ventilation efficiency is 75%.

Table 3.2-4 Sensitivity to drift spacing of 30, 40, 50, 60, and 70 m, for a clay repository with 21-UOX and 32-UOX WPs

21-UOX with 40 GWd/MT burnup in clay

Figure Number	Case Number	Drift Spacing, m		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-14	**21**	**30**		134.6	593		164.1	488
B.3-15	21w	40		116.1	641		145.3	470
B.3-16	21x	50		103.2	641		133.6	432
B.3-17	21y	60		94.0	641		126.6	378
B.3-18	21z	70		87.4	567		122.4	355

32-UOX with 40 GWd/MT burnup in clay

Figure Number	Case Number	Drift Spacing, m		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-19	**25**	**30**		190.7	593		225.2	516
B.3-20	25a	40		162.4	641		196.5	514
B.3-21	25b	50		142.9	641		178.0	468
B.3-22	25c	60		128.8	641		166.3	410
B.3-23	25d	70		118.7	567		159.3	374

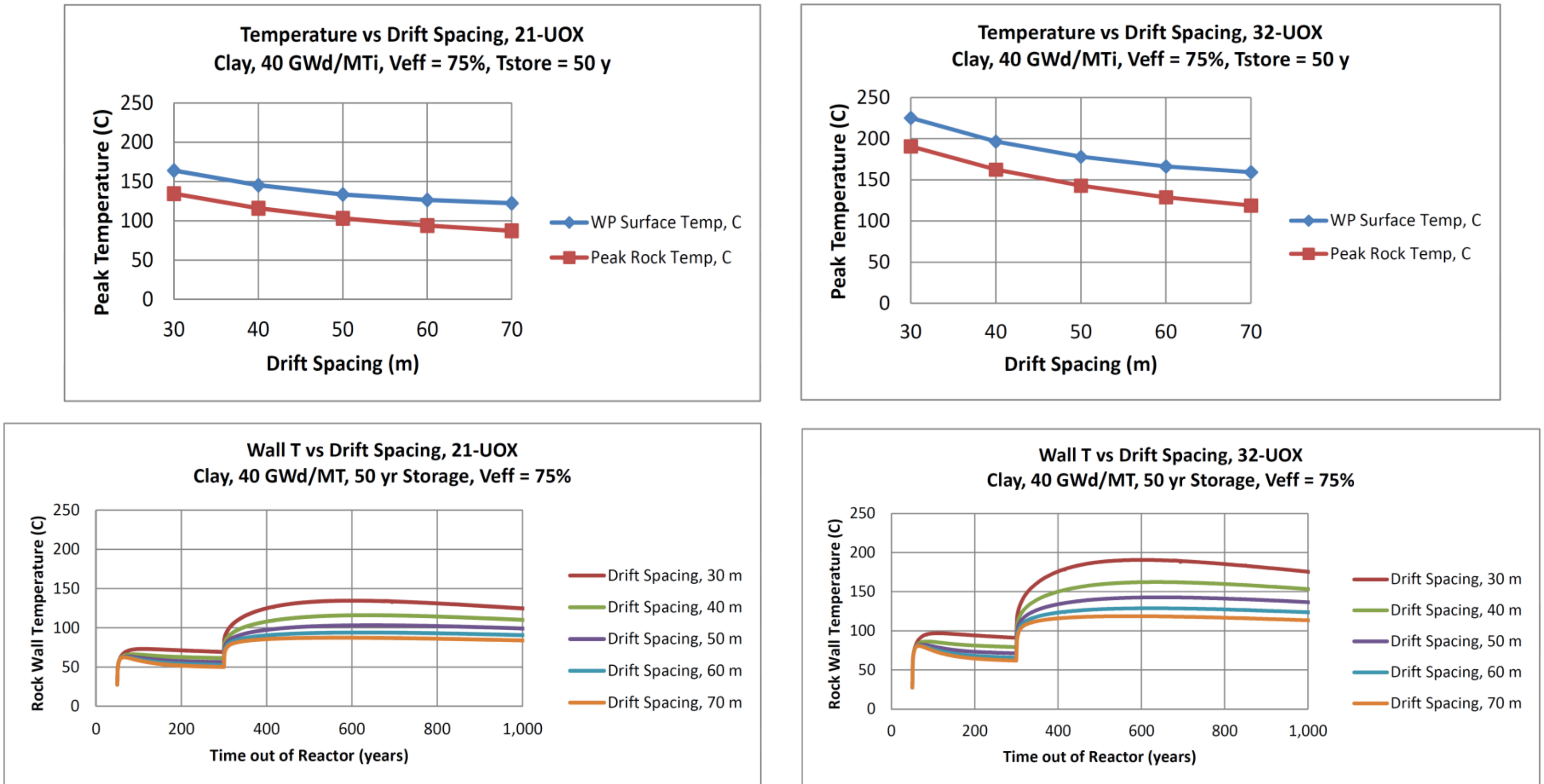


Figure 3.2-4 Effect of drift spacing on peak wall and WP temperatures for a clay repository with large waste packages

For this repository design, increasing the drift spacing will lower temperatures to meet thermal limits, as shown in the top two panes. The bottom two panes show transient rock wall temperatures; the peaks of the curves are the data points on the red curves on the top panes.

3.2.5 Sensitivity to Host Rock Thermal Conductivity

Table 3.2-5 summarizes the peak temperatures and times for the host rock thermal conductivity study, and Figure 3.2-5 presents these results graphically in the top pane, along with the transient temperature results in the lower panes.

This section assumes a nominal volumetric heat capacity typical of clay. All cases use a 21-UOX WP with either 40 or 60 GWd/MT burnup, and also use 50 yr of storage, 250 yr of ventilation at 75% efficiency, and 10 yr of backfill emplacement.

Table 3.2-5 Sensitivity to rock thermal conductivity, assuming a generic host rock with kth = 1, 2, 3, 4, and 5 W/m-K

Figure Number	Case Number	Burnup, GWd/MT	Thermal Conductivity, W/m-K		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-24	57	40	1		182.4	641		209.9	547
B.3-25	58	40	2		125.8	604		155.3	488
B.3-26	59	40	3		101.4	567		132.8	442
B.3-27	60	40	4		87.8	526		120.3	417
B.3-28	61	40	5		78.9	526		112.2	405
B.3-29	62	60	1		217.7	624		252.0	515
B.3-30	63	60	2		147.7	567		185.1	439
B.3-31	64	60	3		118.4	518		157.8	410
B.3-32	65	60	4		101.8	495		142.5	393
B.3-33	66	60	5		90.6	491		132.6	370

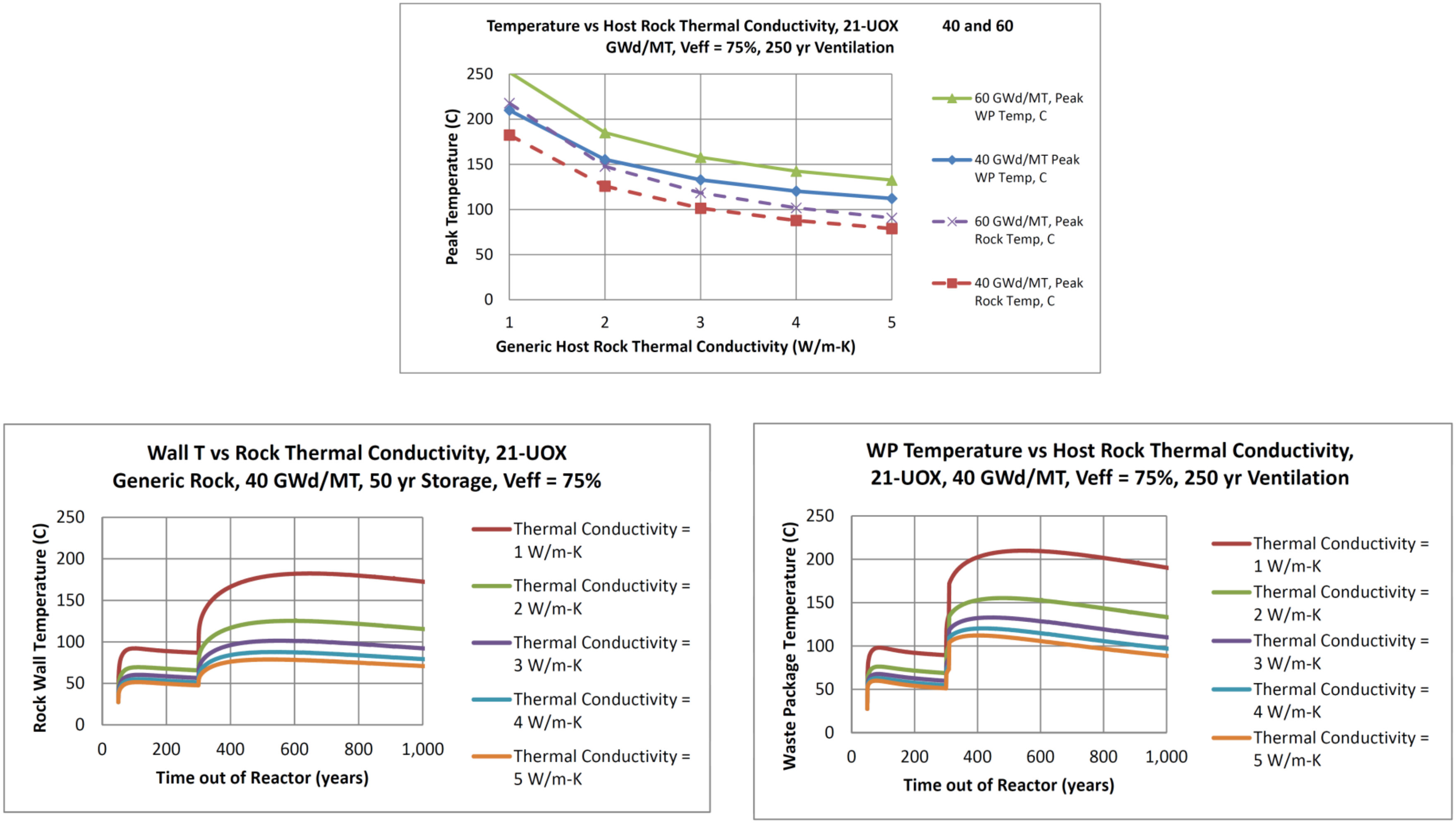


Figure 3.2-5 Generic host rock thermal conductivity sensitivity study with thermal conductivity = 1, 2, 3, 4, and 5 W/m-K

3.2.6 Sensitivity to Backfill Thermal Conductivity

Table 3.2-6 summarizes the peak temperatures and times for the generic backfill thermal conductivity study, and Figure 3.2-6 presents these results graphically in the top pane, along with the transient temperature results in the lower panes. WPs are 21-PWR with 40 GWd/MT burnup. Axial spacing is 10 m and lateral spacing is 30 m.

Table 3.2-6 Sensitivity to backfill thermal conductivity, assuming generic backfill with kth = 1, 2, 3, 4, and 5 W/m-K

Figure Number	Case Number	Burnup, GWd/MT	Backfill Thermal Conductivity, W/m-K		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-34	67	40	1		134.6	593		170.4	488
B.3-35	68	40	2		134.6	593		151.8	535
B.3-36	69	40	3		134.6	593		145.9	554
B.3-37	70	40	4		134.6	593		143.0	567
B.3-38	71	40	5		134.6	593		141.3	567

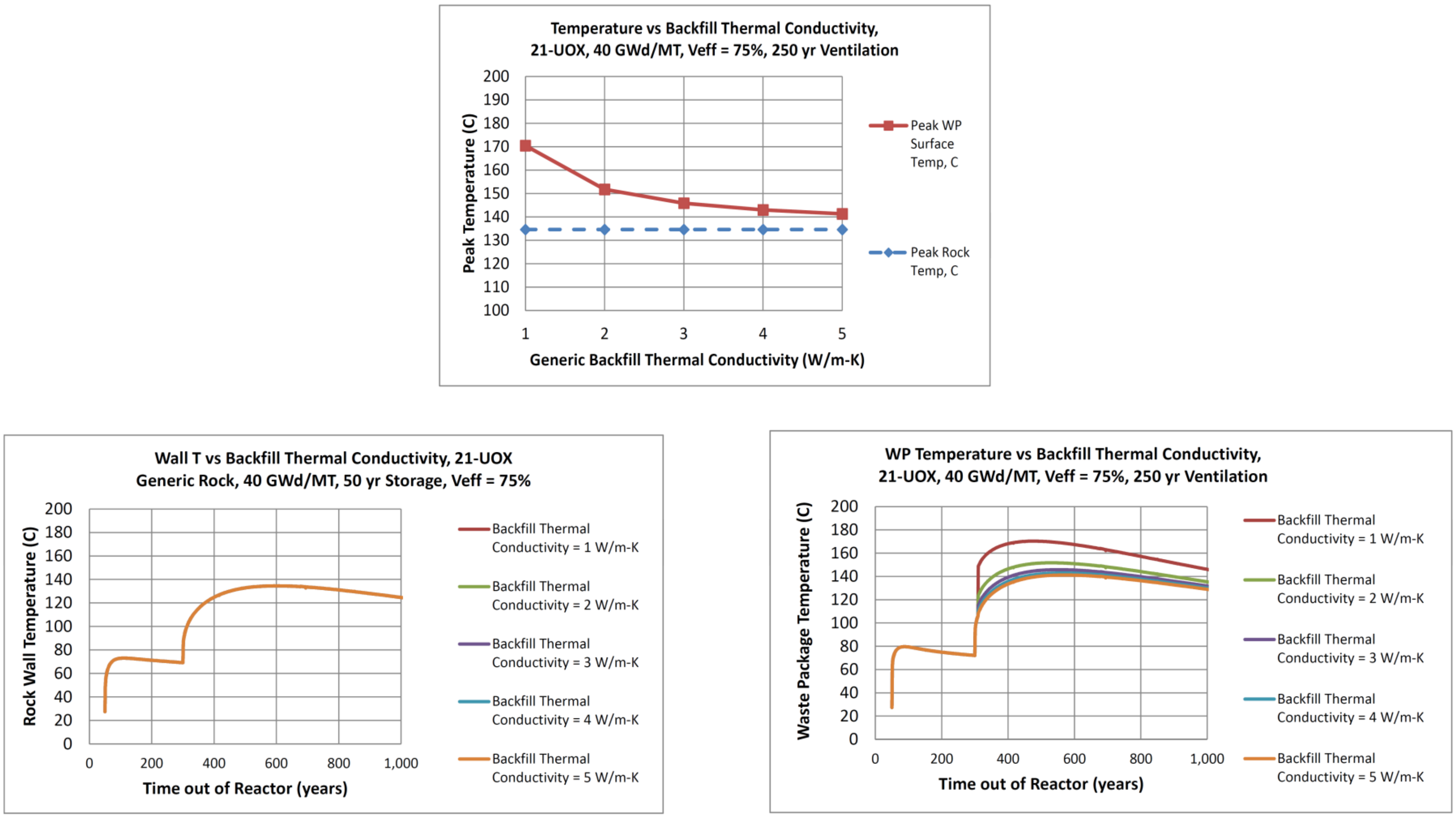


Figure 3.2-6 Generic backfill thermal conductivity sensitivity study with thermal conductivity = 1, 2, 3, 4, and 5 W/m-K

3.2.7 Uncertainty Analysis for Host Rock Thermal Conductivity

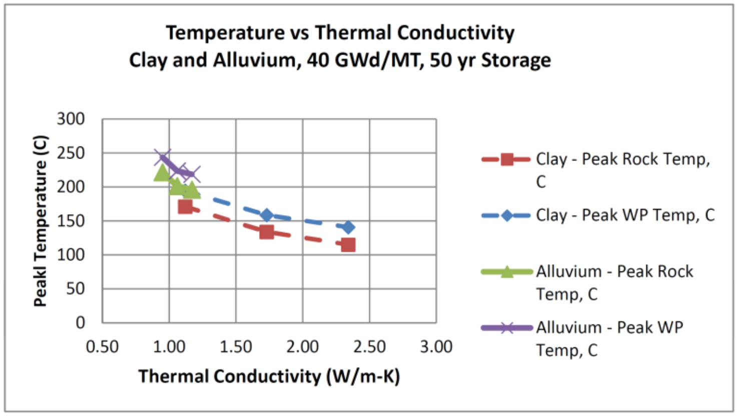
One and two standard deviations in thermal conductivity were calculated for clay and alluvium using the data shown in Figure 3.1-4. The ranges in the published data include three factors: variation from site to site, variation at a particular site, and uncertainty in the measurements themselves. It is normally prudent to look at the sensitivity of dependent variables (such as peak temperatures for a given repository design) using ±2 standard deviations in the independent variables. However, because sites with very low thermal conductivities may be excluded from siting consideration depending on the details of the waste stream and the repository design, considering the range of peak temperatures using ±1 standard deviation may be more appropriate.

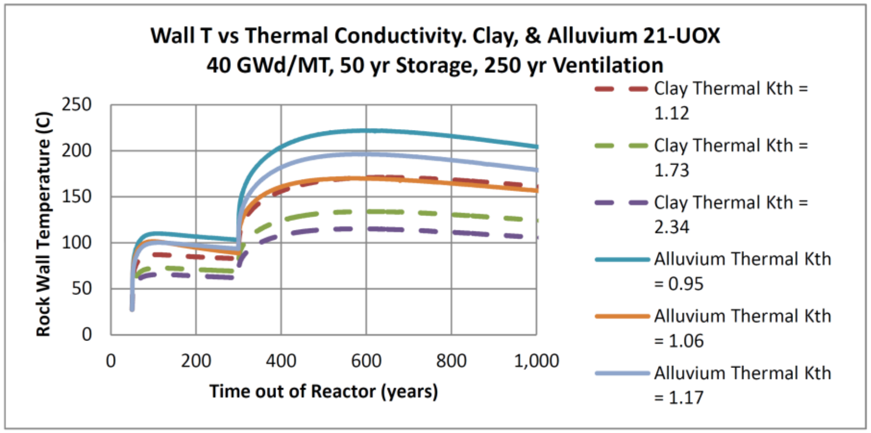
Table 3.2-7 Uncertainty analysis for rock thermal conductivity and rock thermal diffusivity (±1 and ±2 std. dev.) in clay and alluvium

Figure Number	Case Number	Medium	# of standard deviations from the mean	Thermal Conductivity (W/m-K)	Thermal Diffusivity (m^2/sec)		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.4-1	21m	Clay	-2	0.51	1.90E-07		265.2	675		291.2	593
B.4-2	21r	Clay	-1	1.12	4.18E-07		172.1	648		200.0	536
B.4-3	**21**	**Clay**	**Mean**	**1.73**	**6.45E-07**		134.6	593		164.1	488
B.4-4	21s	Clay	+1	2.34	8.72E-07		115.6	592		146.2	464
B.4-5	21n	Clay	+2	2.95	1.10E-06		102.5	567		133.9	442
B.4-6	49a	Alluvium	-2	0.84	5.45E-07		238.5	611		266.5	544
B.4-7	49c	Alluvium	-1	0.95	6.17E-07		222.0	606		250.5	515
B.4-8	**49**	**Alluvium**	**Mean**	**1.06**	**6.88E-07**		201.5	593		230.3	521
B.4-9	49d	Alluvium	+1	1.17	7.59E-07		196.3	592		225.4	521
B.4-10	49b	Alluvium	+2	1.28	8.31E-07		186.2	592		215.6	515

In this sensitivity study, the thermal diffusivity range for each medium only includes the uncertainty in thermal conductivity; the volumetric heat capacity is the nominal value for the medium. These calculations use 50 yr storage time, 250 yr ventilation at 75% efficiency, and 10 yr backfill installation time. Axial and lateral spacing is 10 and 30 m, respectively. WPs are 21-PWR with 40 GWd/MT burnup.

Figure 3.2-7 presents the results for ± 1 standard deviation graphically in the top pane, along with the transient temperature results in the lower panes.





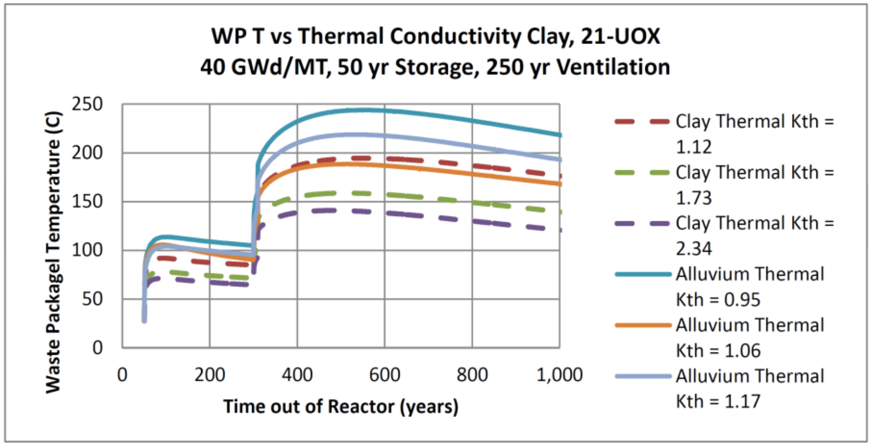


Figure 3.2-7 Generic analysis for rock thermal conductivity and rock thermal diffusivity (± 1 std. dev.) in clay and alluvium

3.3 ANALYSIS OF THE DESIGN TEST CASE DEVELOPED FOR COST ANALYSES

Using the insight gained by the base case analyses and the sensitivity studies presented in Section 3.2 and in Appendix B, a combination of parameters was selected to examine a repository design and operational case for disposal of 21-UOX waste packages. Table 3.3-1 presents the summary of peak temperature values, and Figure 3.3-1 shows the transient temperatures graphically.

These calculations use 50 yr storage time, and either 50 or 100 years of ventilation at 75% efficiency, as well as a post-ventilation 10-yr backfill installation time during which radiation heat transfer continues. They also assume the base case axial spacing of 10 m center-to-center waste package spacing, but with an extended lateral (borehole or drift) spacing of 60 m.

Table 3.3-1 Design Test Case for Cost Analyses: drift spacing = 60 m, 21-UOX, 40 GWd/MT, with 50 and 100 years of ventilation, and varying backfill thermal conductivity

Figure Number	Case Number	Media	Burnup (GWd/MT)	Case Description	T_{store} (yr)	$T_{operate}$ (=T_{store}+T_{vent}) (yr)	Peak Rock Temp, C	Peak Time, yr	Peak WP Surface Temp, C	Peak Time, yr
B.5-1	72	Clay	40	No backfill	50	100	121.3	129	135.2	121
B.5-2	73	Clay	40	backfill kth=2	50	100	121.3	129	172.6	113
B.5-3	73b	Clay	40	backfill kth=1.2	50	100	121.3	129	208.9	110
B.5-4	73a	Clay	40	backfill kth=0.6	50	100	121.3	129	300.0	110
B.5-5	74	Clay	40	r_{DW} = 5.25 m	50	100	100.9	470	**	**
B.5-6	75	Clay	40	No backfill	50	150	107.3	384	115.7	210
B.5-7	76	Clay	40	backfill kth=2	50	150	107.3	384	139.0	177
B.5-8	76b	Clay	40	backfill kth=1.2	50	150	107.3	384	164.0	166
B.5-9	76a	Clay	40	backfill kth=0.6	50	150	107.3	384	228.8	160
B.5-10	77	Clay	40	r_{DW} = 5.25 m	50	150	95.1	562	**	**

** Note that the host rock temperature transient at 3 m depth is independent of the EBS design configuration in the model

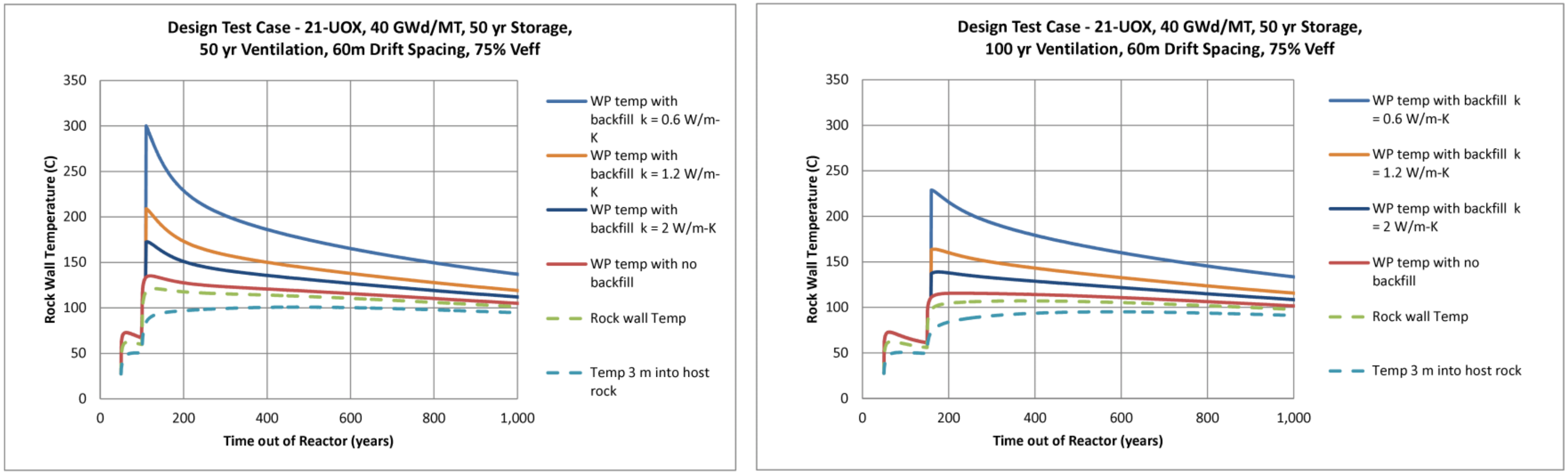


Figure 3.3-1 Design Test Case for Cost Analyses: drift spacing = 60 m, 21-UOX, 40 GWd/MT, with 50 and 100 years of ventilation, and varying backfill thermal conductivity

Table 3.3-2 presents the results for the design test case combining data from 3 different runs. The waste package and rock wall temperatures were calculated as a function of waste package spacing (10, 15, and 20 m). In each case, the drift spacing is 60 m, with 21-UOX, 40 GWd/MT, waste packages, ventilation efficiency of 75%, 10 years to backfill, and backfill thermal conductivity of 1.2 W/m-K. The transient results for these cases are presented in Figure 3.3-2, with individual case transients presented in Appendix B, Section B.5.

Table 3.3-2 Design Test Case for Cost Analyses: drift spacing = 60 m, 21-UOX, 40 GWd/MT, with 50 years of ventilation, backfill thermal conductivity = 1.2 kW/m-K, and varying waste package spacing (10, 15, and 20 m)

Figure Number	Case Number	Media	Waste Package Spacing, m	Backfill Thermal kth W/m-K	T_{store} (yr)	$T_{operate}$ ($=T_{store}+T_{vent}$) (yr)	Peak Rock Temp, C	Peak Time, yr	Peak WP Surface Temp, C	Peak Time, yr
B.5-3	73b	Clay	10	1.2	50	100	121.3	129	208.9	110
B.5-11	73d	Clay	15	1.2	50	100	101.7	123	191.2	110
B.5-12	73c	Clay	20	1.2	50	100	92.9	116	183.6	110

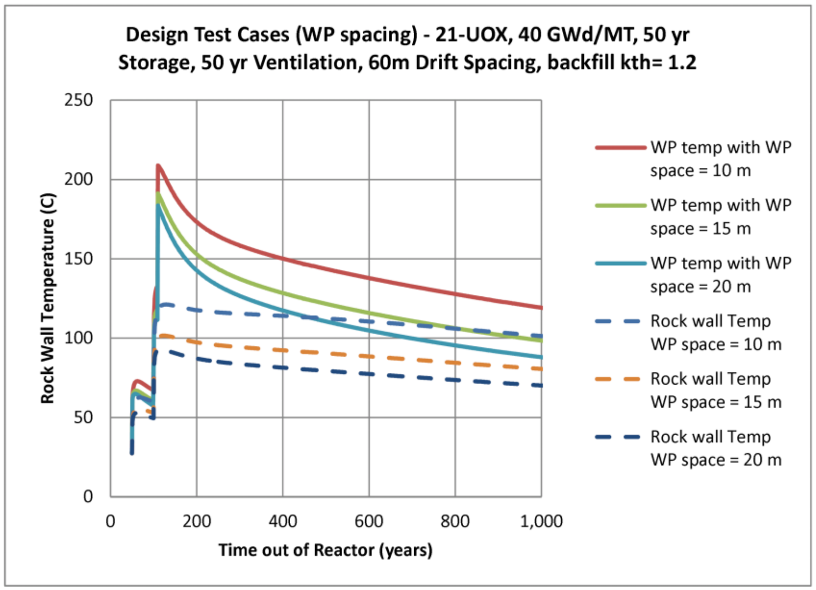


Figure 3.3-2 Design Test Case for Cost Analyses: sensitivity to waste package spacing

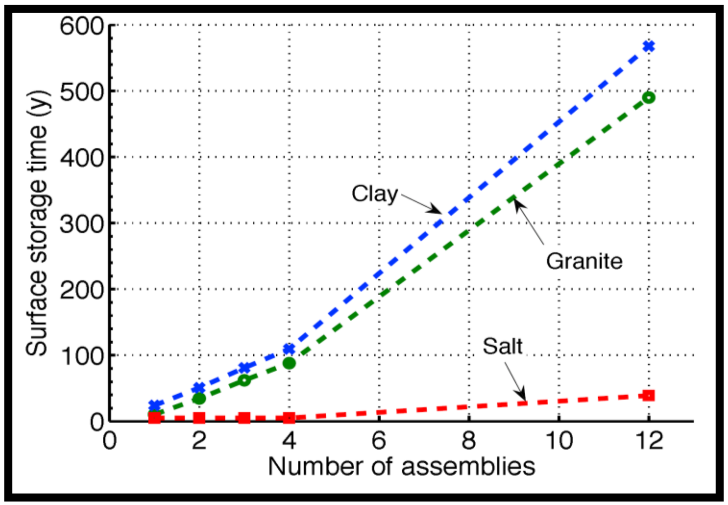
4. SUMMARY AND RECOMMENDATIONS

The base case analyses presented in Section 3.2.1 allow a comparison of the temperature responses for the clay and alluvium design cases in Table 3.2-1 and Figure 3.2-1. The thermal response to the uncertainty in host rock thermal properties for both clay and alluvium is presented in Section 3.2.7. While all of the other sensitivity analyses were performed assuming a clay/shale environment, the relative response in an alluvium environment is similar, and can be approximated by looking at the relative response of clay and alluvium shown in Section 3.2.1 and 3.2.7.

Comparison of Enclosed and Open Mode Repository Design Thermal Results

Figure 4-1 compares selected results from the prior enclosed mode study (Sutton et. al 2011) with open mode results from this study. The left pane in the figure uses WP and borehole spacing of 10 and 30 m, respectively, and uses 60 GWd/MT UOX waste packages. If the temperature limit for the buffer is 100°C, a 4-PWR-assembly waste package can meet the thermal limit in clay if the waste is stored on the surface for 100 years between removal from the reactor flux and emplacement in the repository.

The right pane in the figure has the same repository layout, and has a repository closure time of 300 years. Consider the solid red curve which has the same 60 GWd/MT burnup and 50 yr surface storage time; if we wish to keep the same criteria as applied in the enclosed mode design, i.e., limit the waste package surface temperature to 100°C, the curve crosses that value at a waste package capacity of around 8-PWR-assemblies with repository closure 300 yr after the waste has been removed from the reactor flux (i.e., 50 yr of surface storage and 250 yr of ventilation at 75% efficiency in the repository after emplacement). If the temperature limit could be raised to around 130°C, a 12-PWR waste package could be accommodated in an equivalent open mode repository design.



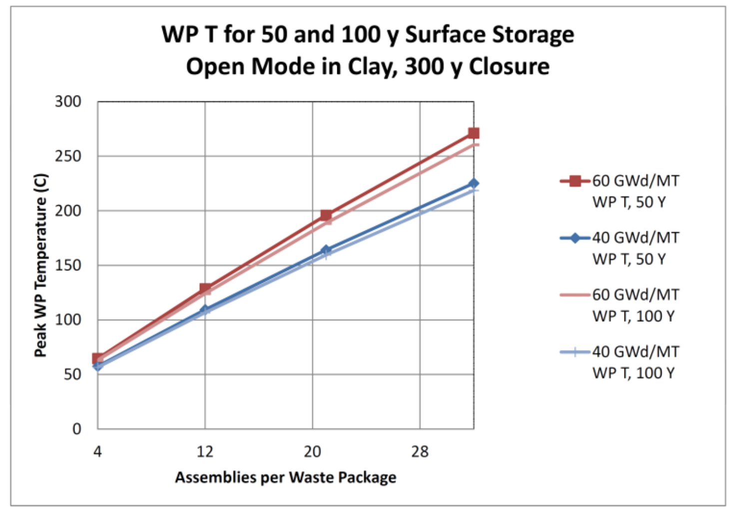


Figure 4-1 Comparison of closed mode (left) and open mode (right)

Comparing these two design points:

- The enclosed mode design requires twice the footprint of the open mode design, for the same inventory. Or, a given repository footprint can dispose of 2 times the waste if the open mode design is used. The cost savings from avoidance of multiple repositories or the avoidance of more extensive underground excavation is expected to be much larger than the cost of constructing and operating the ventilation system.
- Surface storage for the enclosed mode is twice as long (100 yr) as for the open mode (50 yr). This will reduce surface storage costs and environmental impacts if the open mode is used.
- The repository can open 50 yr earlier for the open mode, reducing the worry of hosts of surface storage facilities that they could become de facto repositories.
- The last time the waste packages are handled is at 50 yr for the open mode, which reduces risk that deterioration of the waste could make emplacement and performance assessment more difficult.
- The 250 yr ventilation period before backfilling extends the retrievability option for future generations, which could be invoked if performance confirmation shows unexpected results or if advanced fuel cycles could use the waste as feedstock.

Figure 3.2-1 shows similar figures for the rock wall temperature in clay, and for the waste package and rock wall temperatures in alluvium. If we were to change our acceptance criteria to look at the host rock wall temperature instead of the waste package temperature, then from Figure 3.2-1, applying a 100°C limit in clay would allow a 12-PWR waste package to meet the thermal constraint with 100 years of surface storage. Other changes in the repository layout and engineered backfill properties can be made to accommodate even larger waste packages with the temperature constraints applied at the host rock wall.

The thermal response of the waste package surface temperature and host rock temperature transients were, as expected, significantly different for open emplacement modes and enclosed emplacement modes.

The enclosed emplacement modes analyzed in Sutton et al. 2011 exhibited peak temperatures shortly after emplacement. Figure 5.2-7 of Sutton et al. 2011 (included as the left pane of Figures 1-1 and 4-1 of this report) showed required surface storage times to comply with those thermal constraints for waste package sizes varying from 1 to 12 PWR assemblies of UOX with 60 GWd/MT burnup. It was apparent from those results that enclosed modes of repository design, with acceptable surface storage times, would limit the maximum waste package capacity for UOX disposal to well less than 12 assemblies in clay or granite.

The conclusions from the enclosed modes analysis were tied to the specific thermal constraints, and might result in different conclusions if the thermal constraints could be redefined or relaxed by further investigation or other considerations. The thermal constraints in the various geologic media were primarily derived from the

Engineered Barrier System (EBS) material constraints associated with bentonite buffer materials in clay and granite repository environments (100°C), and with the salt adjacent to the waste package (200°C).

The open mode design concepts evaluated in this report assume a bare waste package, with or without placement of backfill at closure in clay/shale and alluvium host rock designs.

When the Design Test Case for Cost Analyses was defined near the end of the analysis period for open modes, larger waste packages (such as the 21 assembly UOX) and a shorter ventilation period (50 or 100 yr) were chosen. The initial goal of the additional analyses using the large waste package was to keep the peak temperature of the natural barriers (the host rock wall) less than or equal to a range of temperature constraint values, with the following considerations:

- A 100°C thermal limit in clay/shale (or bentonite backfill) is widely accepted to protect the desirable performance assessment properties of clay
- A 120°C thermal limit is probably defensible with more testing, and with an increased licensing risk
- A 140°C thermal limit may not be defensible, would require considerably more testing, and would entail a more difficult licensing case

In practice, it would be possible to keep a portion of the engineered barrier of the backfill material below the temperature constraints for large waste packages and short ventilation periods if the peak wall temperature is lowered to create some margin, and the engineered backfill thermal conductivity is increased.

The tables and figures in Section 3.3 show that with 50 years of surface storage and 50 to 100 years of ventilation system operation, it is possible to keep the rock wall below some of the temperature constraints listed above, using repository layout parameters to compensate for the larger waste package and shorter ventilation time compared to the base case design used in Section 3.2.

As expected, meeting lower temperature constraints is achieved at the expense of higher construction and operating costs. For each geologic medium, the following design and operating parameters can be adjusted in the open mode repository designs to meet the thermal constraints:

- Ventilation system design (thermal efficiency)
- Duration of preclosure operations and ventilation
- Drift or borehole spacing
- Waste package spacing
- Engineered backfill thermal conductivity

In clay/shale, Figure 3.3-1 and Table 3.3-1 show that we can meet the 120°C wall temperature constraint with the repository layout described in Hardin et al. 2012c (10 m WP spacing and 60 m borehole spacing) with 50 years of ventilation, and come close to the 100°C constraint with 100 years of ventilation.

If we are willing to have a sacrificial core of clay around the emplacement drift that exceeds the temperature constraint, and apply the temperature constraint at 3 m into the host rock, the 100°C constraint is only slightly exceeded at that depth with 50 years of ventilation, and is met with a small margin with 100 years of ventilation, as shown in Figure 3.3-1 and Table 3.3-1.

Figure 3.3-2 shows that if we are willing to increase the repository footprint and cost by changing the waste package spacing from 10 m to 15 m, then the 100°C temperature constraint at the wall can be met with 50 years of ventilation.

5. References

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APPENDIX A - MATHEMATICAL MODELS

A.1 INTRODUCTION

A combination of transient heat transfer analytical solutions for a finite line source, a series of point sources, and a series of parallel infinite line sources were combined with a quasi-steady-state multi-layered cylindrical solution to simulate the temperature response of a deep geologic radioactive waste repository with multi-layered natural and engineered barriers. The model development and equations are documented in Appendix G of Sutton et al. 2011.

Modifications of the analytical model included

- A radiation heat transfer model for the open air space prior to backfill, based on infinite concentric cylinders
- A ventilation system model with assumed fixed value for the ventilation thermal efficiency, for a specified ventilation period
- A backfill thermal conduction model replacing the radiation model after backfill has been added (with radiation heat transfer but no ventilation during the backfill installation period).

The host rock thermal transient temperature response contributions from the point sources, finite line sources, and infinite line sources were added by superposition. The convolution integral equations from Sutton et al. 2011 were:

Equation A.1-1:

$$T_{point}(t,r) = \frac{1}{8\cdot\rho\cdot Cp\cdot(\pi\cdot\alpha)^{\frac{3}{2}}}\cdot\int_0^t \frac{q(t')}{(t-t')^{\frac{3}{2}}}\cdot e^{\frac{-r^2}{4\cdot\alpha\cdot(t-t')}}\,dt'$$

Equation A.1-2:

$$T_{line}(t,x,y,z) = \frac{1}{8\cdot\pi\cdot k}\cdot\int_0^t \frac{q_L(t')}{t-t'}\cdot e^{\frac{-\left(x^2+z^2\right)}{4\cdot\alpha\cdot(t-t')}}\cdot\left[\operatorname{erf}\left[\frac{1}{2}\cdot\frac{\left(y+\frac{L}{2}\right)}{\sqrt{\alpha\cdot(t-t')}}\right]-\operatorname{erf}\left[\frac{1}{2}\cdot\frac{\left(y-\frac{L}{2}\right)}{\sqrt{\alpha\cdot(t-t')}}\right]\right]dt'$$

Equation A.1-3:

$$T_{infinite\_line}(t,x,z) = \frac{1}{4\cdot\pi\cdot k}\cdot\int_0^t \frac{q_L(t')}{t-t'}\cdot e^{\frac{-\left(x^2+z^2\right)}{4\cdot\alpha\cdot(t-t')}}\,dt'$$

Where

α	= thermal diffusivity, $m^2/s = k/(\rho\text{-}C_p)$
C_p	= specific heat, kJ/kg-K
k	= thermal conductivity, W/(m-K)
L	= length of the finite line source, m
q_L	= heat per unit length, W/m
q	= heat, W
r	= radius, m
ρ	= density, kg/m^3

These equations are applied to the repository layout of heat sources shown conceptually in Figure 3.1-2, with a single central finite line source (waste package) surrounded axially on either side by four point sources (representing adjacent waste packages), and laterally on either side by four infinite line sources (representing adjacent emplacement drifts).

In the enclosed mode repository designs, which were conduction-only cases, the waste package surface and EBS transient temperatures were calculated using the quasi steady-state approach. At each point in time, the steady-state heterogeneous model, described in Section G.4 of Sutton et al. 2011, was used to calculate the waste package surface temperature, assuming the transient rock temperature at the calculation radius and the waste package heat load as boundary conditions.

In the current analysis a similar approach is taken, however the temperature rise across the air gap (included during preclosure ventilation) is by thermal radiation instead of thermal conduction. After backfilling the emplacement drifts in the open mode designs, the temperature calculations revert to the conduction-only case, with the temperature rise across the former air gap now calculated using the thermal resistance of the backfill layer.

A.2 Thermal Radiation Heat Transfer Model

The modeling of thermal radiation heat transfer is greatly simplified by assuming infinite concentric cylinders, since the view factor from the inner cylinder to the outer cylinder, equals one. This is considered a reasonable approximation for evaluating the temperature at the drift wall adjacent to a waste package.

The equation for the radiation heat transfer coefficient h_{rad} is taken from Incropera and DeWitt, Table 13.3 for concentric infinite cylinders (based on the inner surface as the heat source), and is also referenced in the YMP *Ventilation Model and Analysis Report*, page 6-8 (BSC 2004). The same modeling approach using infinite concentric cylinders was also applied in *Thermal Analysis of the Supercontainer Concept 2D Axisymmetric Heat Transport Calculations*, Section 6.4.3. page 34, equation 29 (Weetjens and Silien 2005).

Equation A.2-1:

$$h_{rad\_infinite}(r_i, r_o, \varepsilon_i, \varepsilon_o) := \frac{\sigma}{\dfrac{1}{\varepsilon_i} + \left(\dfrac{1-\varepsilon_o}{\varepsilon_o}\right)\cdot\dfrac{r_i}{r_o}}$$

Where

$h_{rad\_infinite}$ has units of W/(m^2-K^4)

ε_i = emissivity of the inner surface (dimensionless)

ε_o = emissivity of the outer surface (dimensionless)

r_i = radius of the inner cylinder, m

r_o = radius of the outer cylinder, m

σ = Stefan Boltzmann constant = $5.670\cdot10^{-8}$ W/ (m^2-K^4)

The outer surface emissivity (ε_o) was chosen to represent either a dirty steel liner, bare rock, or a shotcrete lined/supported drift opening. The inner surface emissivity (ε_i) was chosen to represent the waste package metal surface in a stably oxidized condition. The value was chosen to approximate both copper and steel surfaces.

$$\varepsilon_o = \varepsilon_{wall} = 0.9 \qquad \varepsilon_I = \varepsilon_{WP} = 0.6$$

The basis for the wall and waste package emissivity values assumed is from *Fundamentals of Heat and Mass Transfer* (Incropera and DeWitt 1996), Table A-11, which shows a range of 0.88 to 0.93 based on hemispherical emissivity of rock at around 300 K. This range is corroborated by the "Heat Transmission" section of *Perry's Chemical Engineers Handbook* (Perry's Handbook 1984), Table 10-17 (pages 10-51 to 10-52) for normal emissivity of rough silica and rough fused quartz, ranging from 0.8 to 0.93.

The calculation of the temperature of the waste package, given the transient temperature of the host rock, which is calculated using the model described in Appendix A.1, and the central waste package heat source (W/m) is modeled in Mathcad as:

Equation A.2-2:

$$q_{L\_rad\_infinite}(r_i, r_o, \varepsilon_i, \varepsilon_o, T_{cold}, T_{hot}) := h_{rad\_infinite}(r_i, r_o, \varepsilon_i, \varepsilon_o) \cdot (2 \cdot \pi \cdot r_i)\left(T_{hot}{}^4 - T_{cold}{}^4\right)$$

Where $q_{L\_rad\_infinite}$ is the linear heat load (W/m), calculated by dividing the waste package heat source by the waste package length, T_{hot} is the waste package surface temperature, and T_{cold} the host rock wall temperature.

During the 10 years assumed for closure operations, natural convection would occur in addition to radiative coupling, so waste package temperatures would be slightly less than calculated. A previous study concluded that during such heating conditions, thermal radiation would be the dominant mode of heat transfer (BSC 2005).

A.3 VENTILATION SYSTEM MODEL

Section 6.3.5 of the YMP *Ventilation Model and Analysis Report* (BSC 2004) defines both instantaneous ventilation thermal efficiency, and integrated ventilation thermal efficiency.

Because the ventilation air temperature increases as the air flows from the inlet of the emplacement drift to the exit into the exhaust main, and the decay heat sources are a function of time, the instantaneous ventilation efficiency is both a function of time and distance from the entrance and is defined by:

Equation A.3-1:

$$\eta(t,x) \equiv \frac{Q_{air}(t,x)}{Q_s(t)}$$

Where

$\eta(t,x)$	= instantaneous ventilation efficiency (dimensionless)
Q_{air}	= heat transferred by natural and forced convection to the air from the waste package and drift wall surfaces (W/m)
Q_s	= heat generated by the waste package (W/m)
t	= time since ventilation began
x	= distance from the drift entrance (m)

It also defines integrated ventilation efficiency as:

Equation A.3-2:

$$\eta_{\text{integrated}} \equiv \frac{\int_0^b \left[\int_0^a Q_{air}(t,x)\cdot dx \right] dt}{x \cdot \int_0^b Q_s(t)\cdot dt}$$

Where

$\eta_{\text{integrated}}$	= integrated ventilation efficiency (dimensionless)
a	= limit of integration in terms of the total drift length
b	= limit of integration in terms of the total ventilation duration

The integrated ventilation thermal efficiency calculated in BSC 2004 was 86%. The ventilation thermal efficiency assumed in the current analysis (V_{eff}) is integrated ventilation efficiency, and in the base cases defined in Table 3.2-1, is assumed to be a constant value of 75%.

A.4 Backfill Properties and Assumptions

Bentonite is often used in European high-level radioactive waste repository design concepts because of its low hydraulic permeability and sealing properties, and has been proposed for both buffer and backfill applications.

The addition of quartz sand has been considered to provide increased structural strength (Pakbaz and Khayat 2004), and to provide increased thermal conductivity (Jobmann and Buntebarth 2009).

Figure 2, of *The Effect of Sand on Strength of Mixtures of Bentonite-Sand* (Pakbaz and Khayat 2004), shows that the unconfined compressive strength of bentonite can be increased by around 50%, with the addition of 30% sand. The effect peaks around 50% sand mixtures, and then starts to decrease at higher percentages.

Figure 3 of *Influence of Graphite and Quartz Addition on the Thermo-Physical Properties of Bentonite for Sealing Heat-Generating Radioactive Waste* (Jobmann and Buntebarth 2009), shows that the addition of 30% sand can effectively double the thermal conductivity of dry bentonite, from 0.6 W/m-K to 1.2 W/m-K.

The backfill material assumed in all of the base cases and most of the sensitivity studies in this report assume a 70% bentonite / 30% quartz sand mixture.

The results of a sensitivity study of the effects of using a generic engineered backfill (backfill mixture undefined) with thermal conductivity ranging from 1 to 5 W/m-K is documented in Section 3.2-6, and Appendix B.3-5.

APPENDIX B - THERMAL ANALYSIS

B.1 INTRODUCTION

The assumptions, inputs, models and solutions for the thermal behavior in clay, and alluvium are documented in Section 3 and Appendix A of this report.

The results in Section B.2 provide the temperature transients associated with the Open Mode clay and alluvium cases. The transient plots include two types: 1) transient temperatures at the host rock wall surface, the liner inner surface and the waste package surface, and 2) transients showing the contribution of the central waste package, adjacent waste packages, and adjacent drifts/boreholes to the rock wall temperature.

The results in Section B.3 provide the temperature transients for several sensitivity and uncertainty analyses as follows:

- B.3.1 – Sensitivity to ventilation system thermal efficiency, including efficiencies of 50, 60, 70, 80, and 90%, in addition to the base case of 75%. These cases used 50 yr storage, 250 yr ventilation, 10 yr backfill emplacement, and 21-UOX WPs with 40 GWd/MT burnup, in clay.
- B.3.2 – Sensitivity to ventilation system operational period, including ventilation periods of 50, 100, 150, and 200 years, in addition to the base case of 250 years. These cases used 50 yr storage, and 10 yr backfill emplacement, 90% ventilation thermal efficiency, and 21-UOX WPs with 40 GWd/MT burnup, in clay.
- B.3.3 – Sensitivity to drift/borehole spacing (i.e., lateral spacing), including spacings of 40, 50, 60, and 70 m, in addition to the base case of 30 m. These cases used 50 yr storage, 250 yr ventilation at 75% efficiency, 10 yr backfill emplacement, and both 21-UOX and **32-UOX WPs** with 40 GWd/MT burnup, in clay.
- B.3.4 – Sensitivity to generic host rock thermal conductivity and thermal diffusivity (with diffusivity based on nominal volumetric heat capacity), including conductivities of 1, 2, 3, 4, and 5 W/m-K, which envelope the base cases of 1.75 W/m-K for clay (Cases 21 and 23) and 1.1 W/m-K for alluvium (Cases 49 and 51). The generic host rock cases used 50 yr storage, 250 yr ventilation at 75%, 10 yr backfill emplacement, and 21-UOX WPs with 40 and 60 GWd/MT burnup, as in the medium-specific base cases.

The results in Section B.4 provide the temperature transients for thermal conductivity uncertainty analyses for clay and alluvium based on the evaluations performed in *Parameter Uncertainty for Thermal Analysis* (Hardin et al. 2012b).

B.2 Temperatures for Open Mode Base Cases in Clay and Alluvium

Table B.2-1 lists the cases used in the main study. Additional sensitivity and uncertainty cases are shown in Appendices B.3 and B.4.

Table B.2-1 List of cases used in the main study. Independent variables are geologic medium, burnup, WP capacity, and storage time

All cases use: 10 m of axial spacing and 30 m of lateral (drift or borehole) spacing; a ventilation efficiency of 75%; ventilation duration extends out to 300 yr (either 250 or 200 yr, depending on the storage time); and the closure time to install backfill is 10 yr (with no ventilation during that period). Bold font is used to highlight which variables change from case to case, and shading is used to highly base cases used for sensitivity studies.

Figure Number	Case Number	Medium	Burnup (GWd/MT)	WF	WP (PWR)	Tstore
B.2-1	13	Clay	40	UOX	4	50
B.2-2	14	Clay	40	UOX	4	**100**
B.2-3	15	Clay	**60**	UOX	4	50
B.2-4	16	Clay	**60**	UOX	4	**100**
B.2-5	17	Clay	40	UOX	**12**	50
B.2-6	18	Clay	40	UOX	**12**	**100**
B.2-7	19	Clay	**60**	UOX	**12**	50
B.2-8	20	Clay	**60**	UOX	**12**	**100**
B.2-9	21	Clay	40	UOX	21	50
B.2-10	22	Clay	40	UOX	21	**100**
B.2-11	23	Clay	**60**	UOX	21	50
B.2-12	24	Clay	**60**	UOX	21	**100**
B.2-13	**25**	Clay	40	UOX	**32**	50
B.2-14	26	Clay	40	UOX	**32**	**100**
B.2-15	27	Clay	**60**	UOX	**32**	50
B.2-16	28	Clay	**60**	UOX	**32**	**100**
B.2-17	41	**Alluvium**	40	UOX	4	50
B.2-18	42	**Alluvium**	40	UOX	4	**100**
B.2-19	43	**Alluvium**	**60**	UOX	4	50
B.2-20	44	**Alluvium**	**60**	UOX	4	**100**
B.2-21	45	**Alluvium**	40	UOX	**12**	50
B.2-22	46	**Alluvium**	40	UOX	**12**	**100**
B.2-23	47	**Alluvium**	**60**	UOX	**12**	50
B.2-24	48	**Alluvium**	**60**	UOX	**12**	**100**
B.2-25	49	Alluvium	40	UOX	21	50
B.2-26	50	**Alluvium**	40	UOX	21	**100**
B.2-27	51	**Alluvium**	**60**	UOX	21	50
B.2-28	52	**Alluvium**	**60**	UOX	21	**100**
B.2-29	53	**Alluvium**	40	UOX	**32**	50
B.2-30	54	**Alluvium**	40	UOX	**32**	**100**
B.2-31	55	**Alluvium**	**60**	UOX	**32**	50
B2-32	56	**Alluvium**	**60**	UOX	**32**	**100**

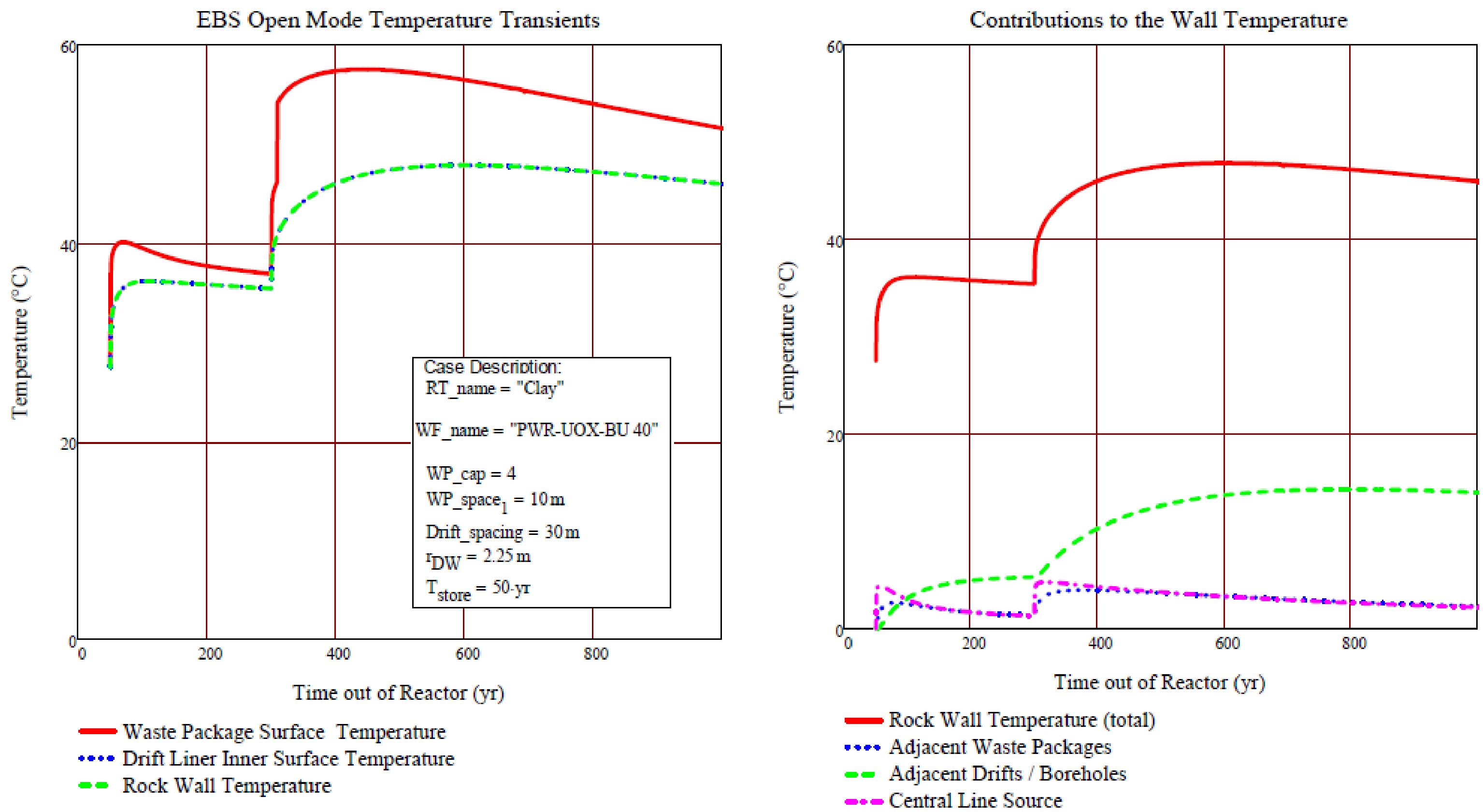


Figure B.2-1 Case 13 - Clay medium, 4-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr

For other parameters, see Base Case 21 in Figure B.2-9.

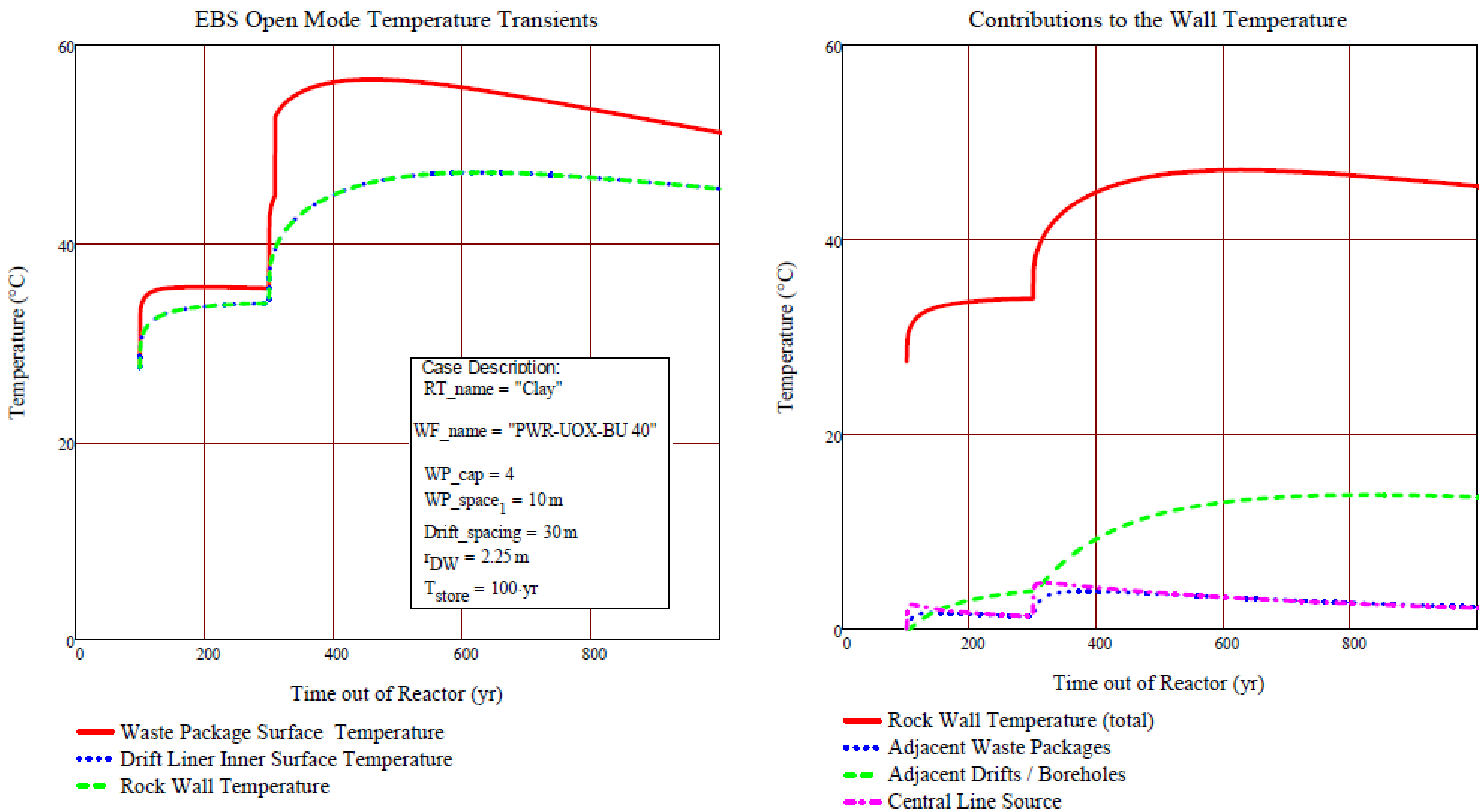


Figure B.2-2 Case 14 - Clay medium, 4-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

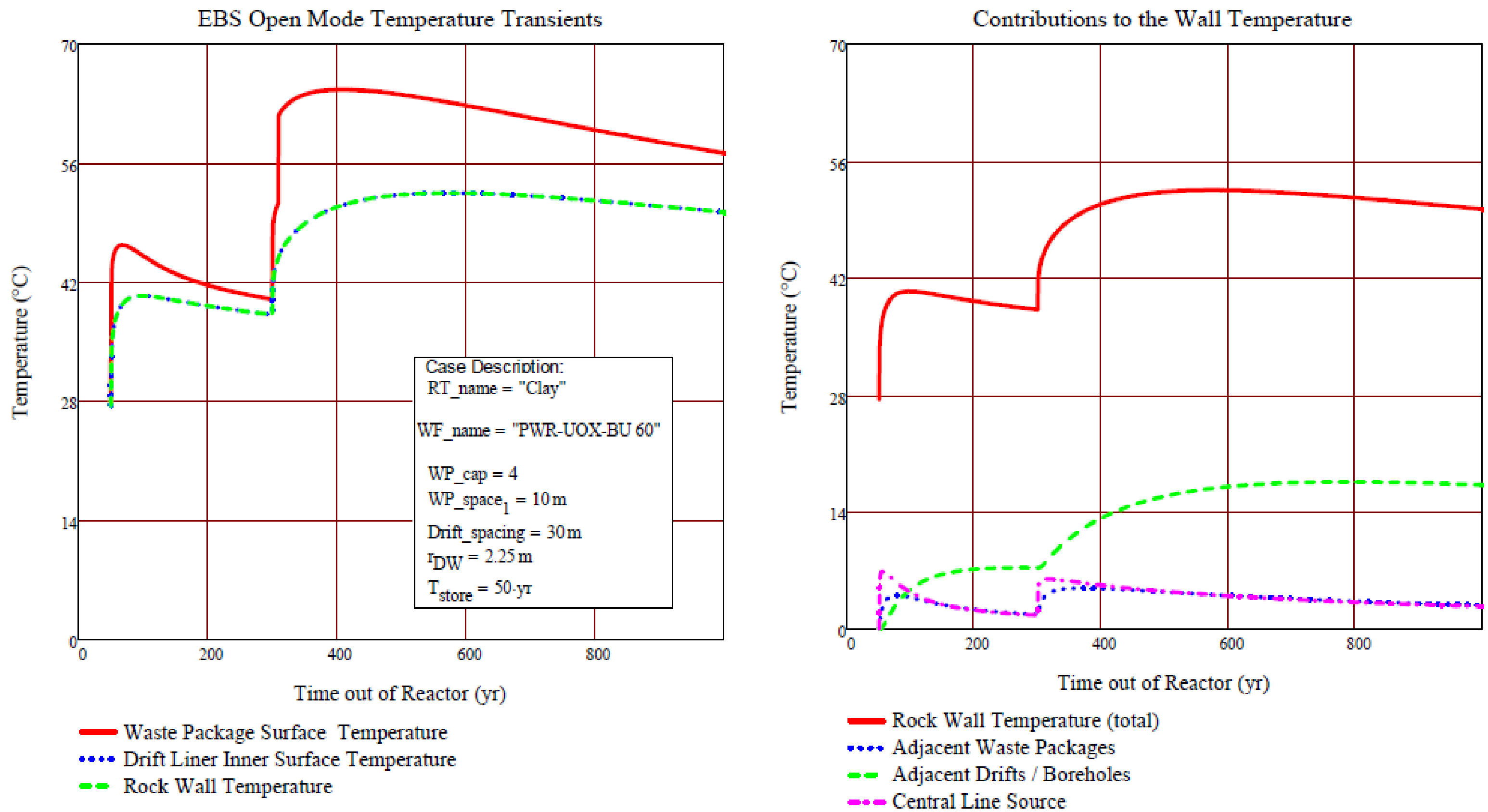


Figure B.2-3 Case 15 - Clay medium, 4-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

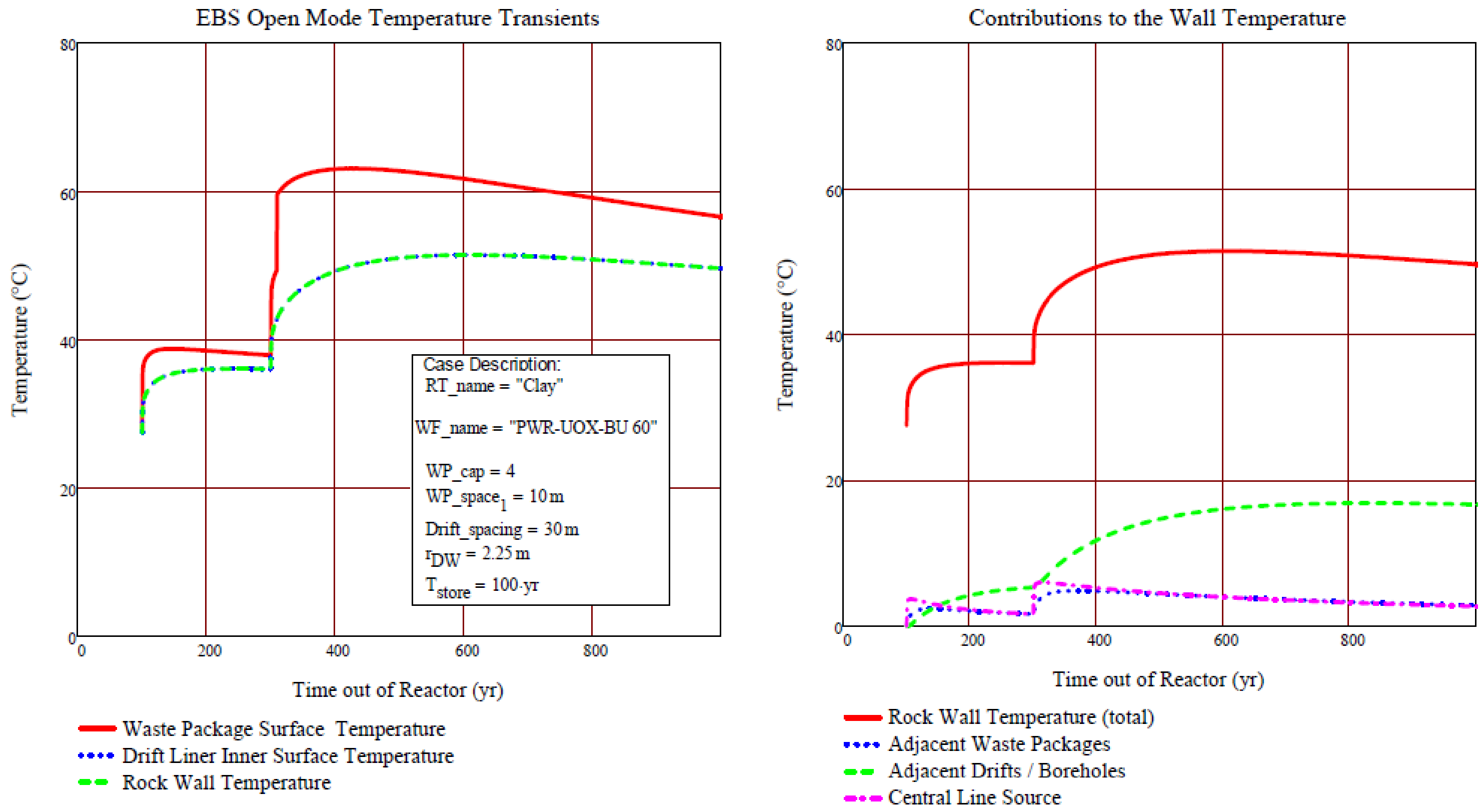
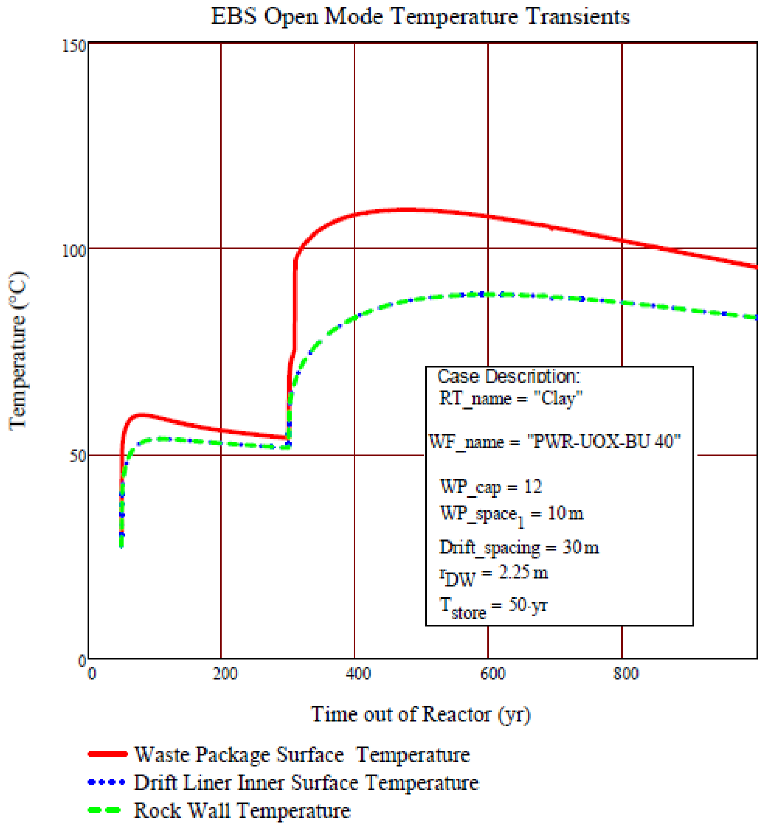


Figure B.2-4 Case 16 - Clay medium, 4-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.



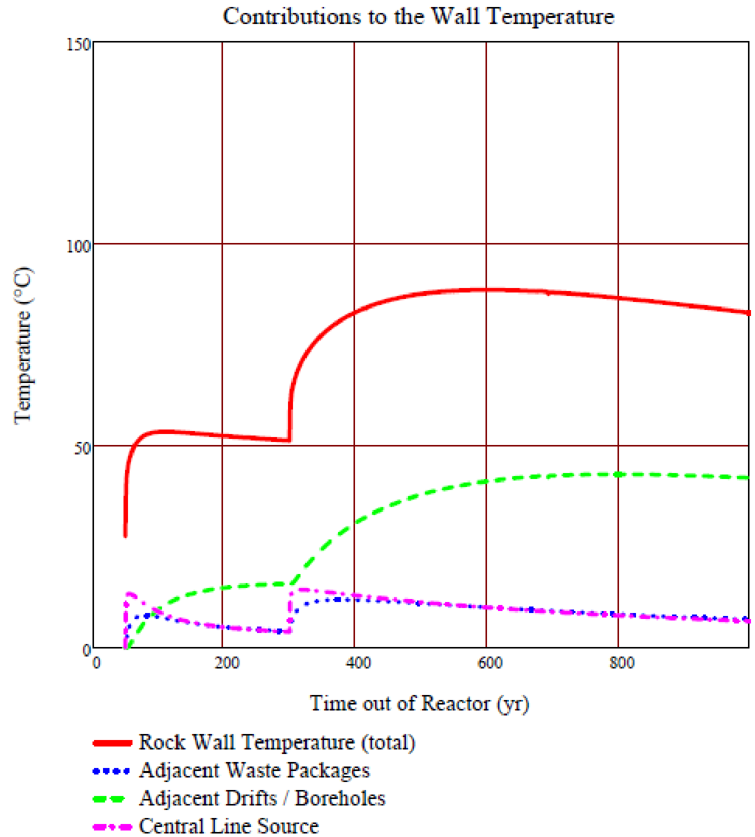


Figure B.2-5 Case 17 - Clay medium, 12-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr. For other parameters, see Base Case 21 in Figure B.2-9.

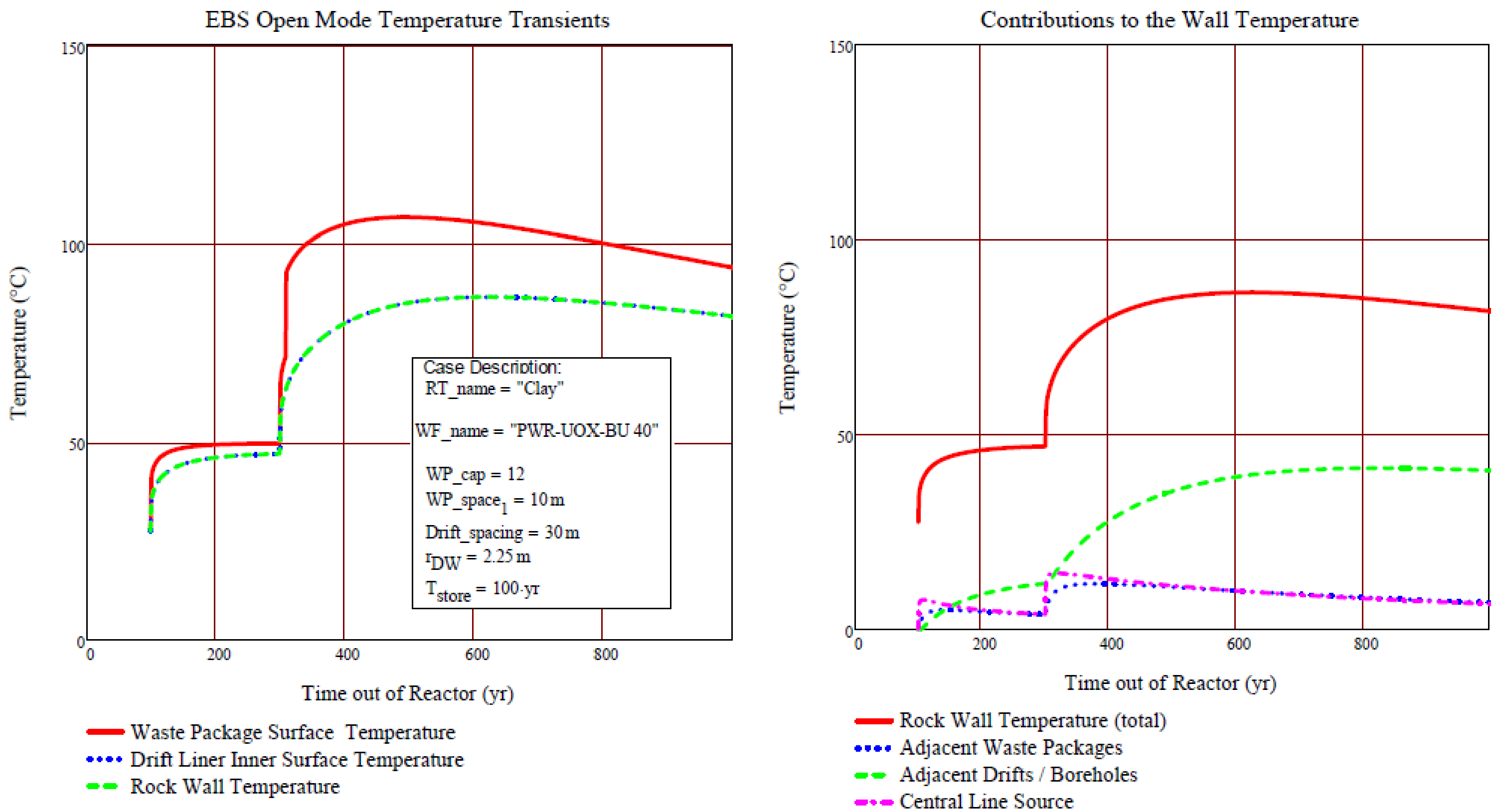
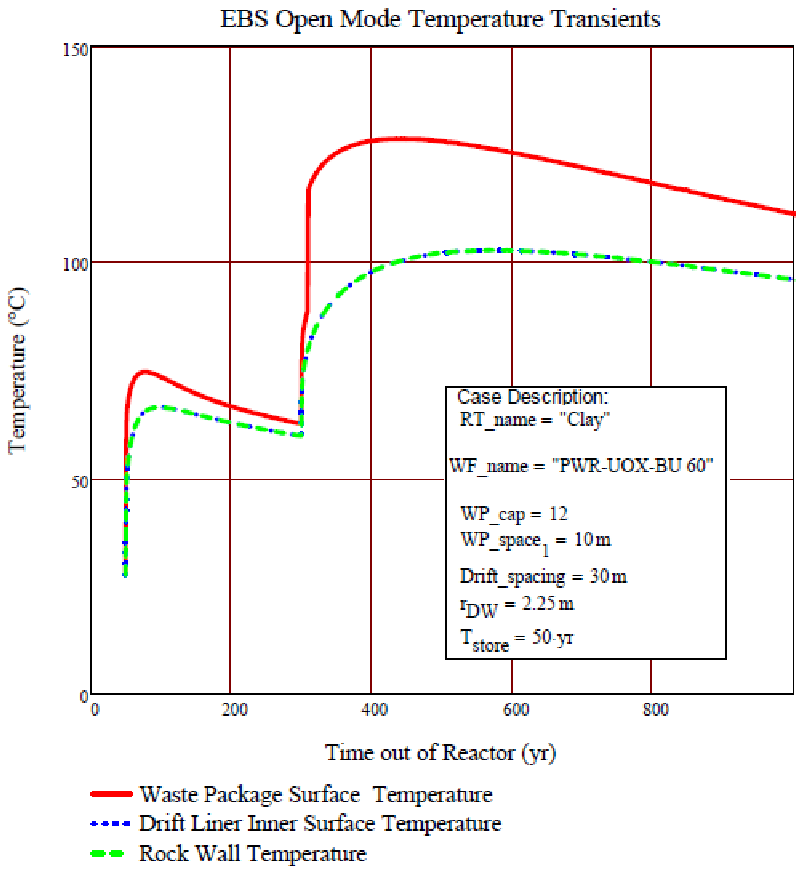


Figure B.2-6 Case 18 - Clay medium, 12-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.



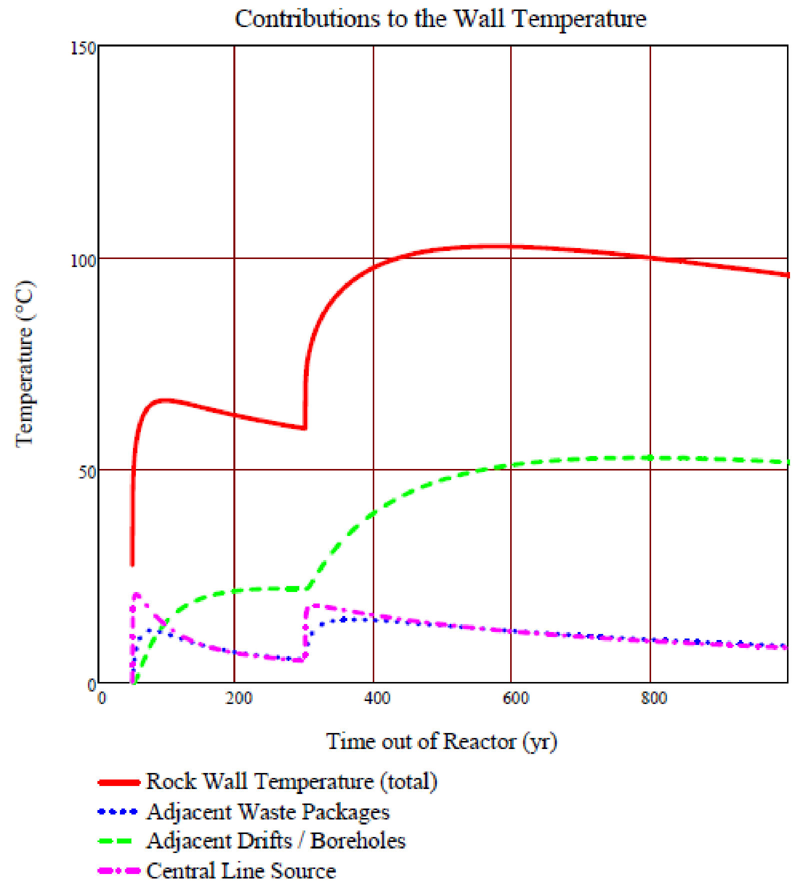


Figure B.2-7 Case 19 - Clay medium, 12-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

See Base Case 21 in Figure B.2-9 for other parameters.

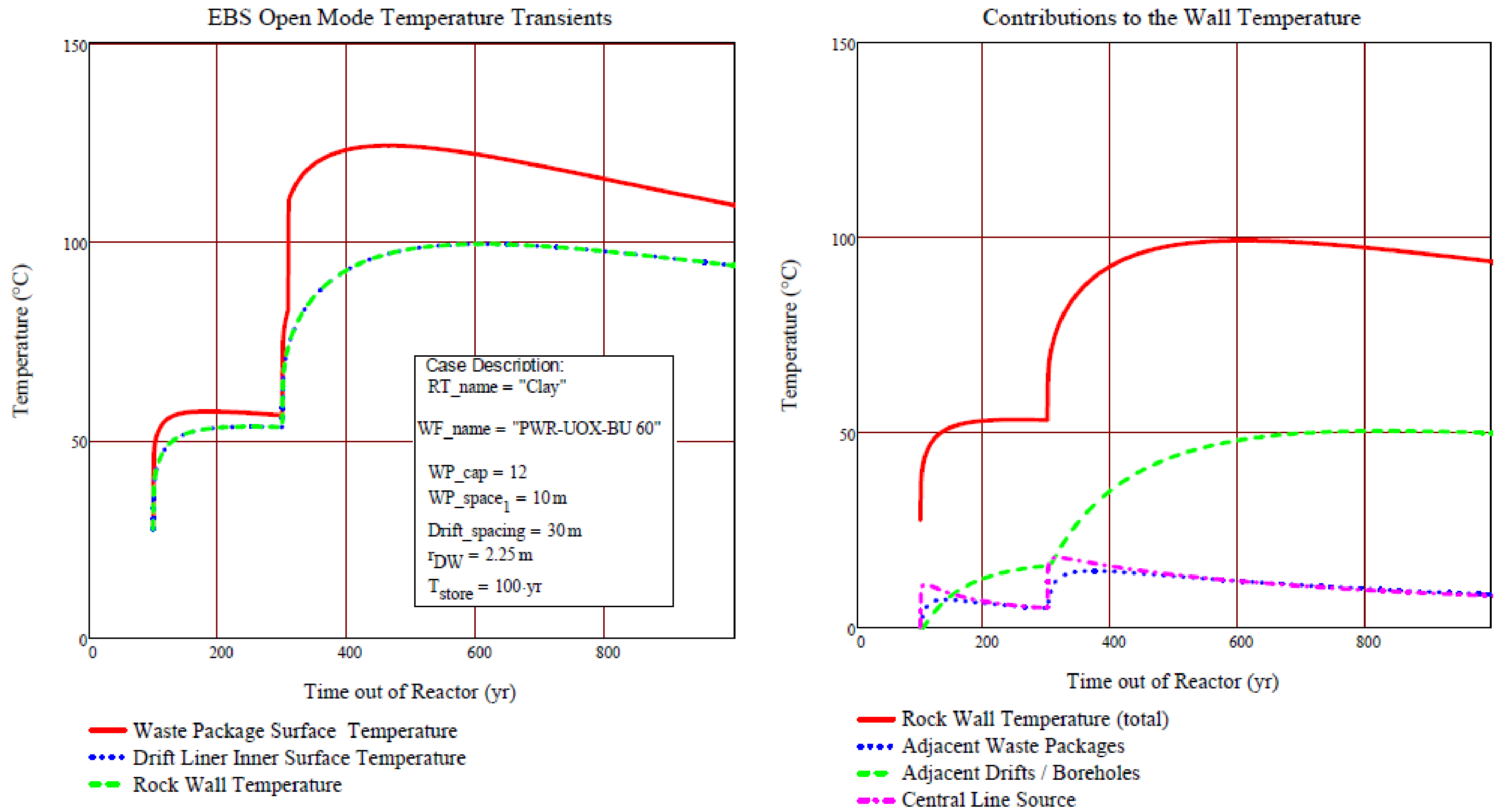


Figure B.2-8 Case 20 - Clay medium, 12-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

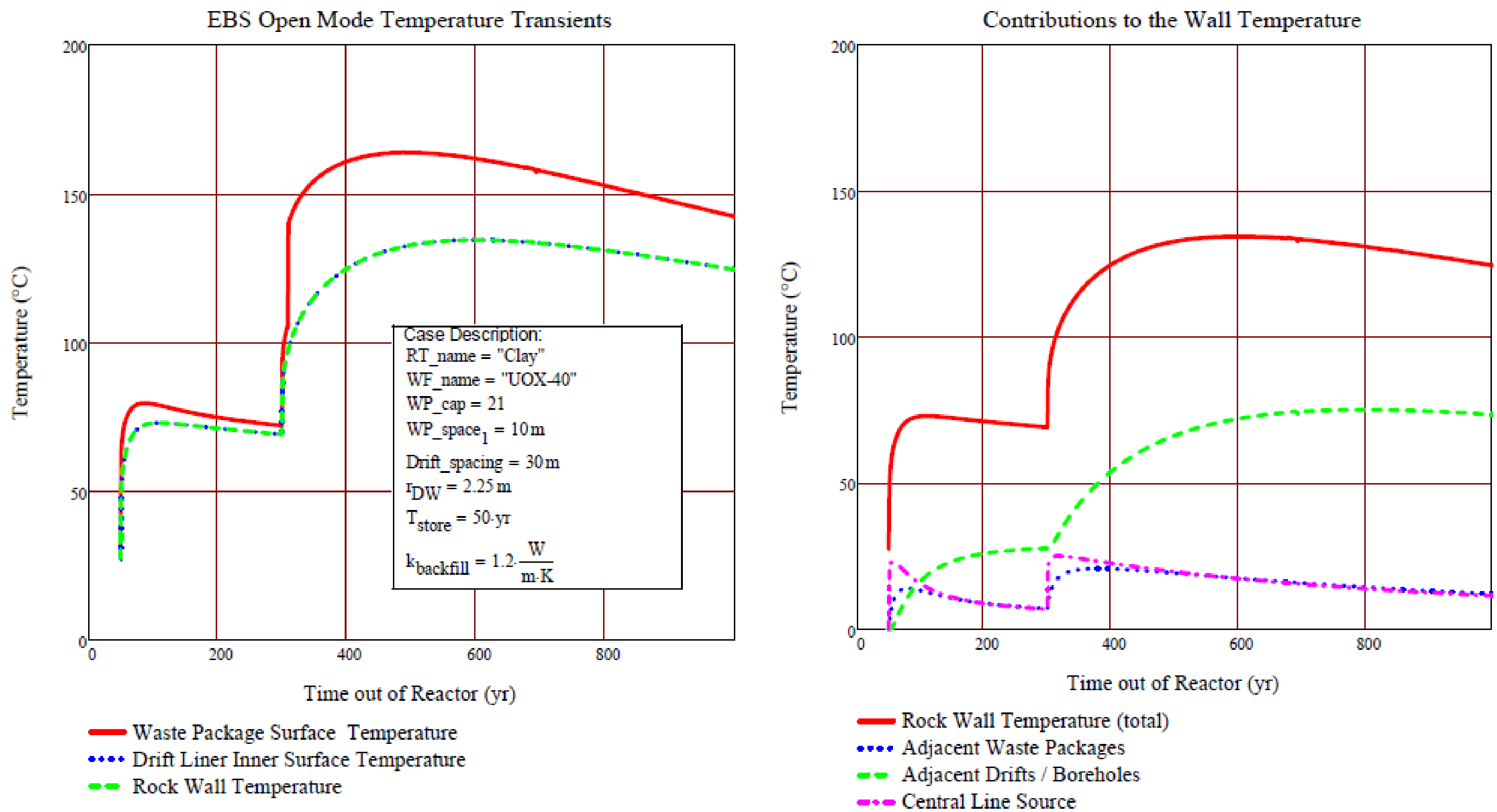


Figure B.2-9 Case 21 - Clay medium, 21-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr.

This is one base case for this Appendix B.2 and is also the Base Case for the ventilation efficiency sensitivity study in Appendix B.3.1 and the uncertainty analysis in Appendix B.4.

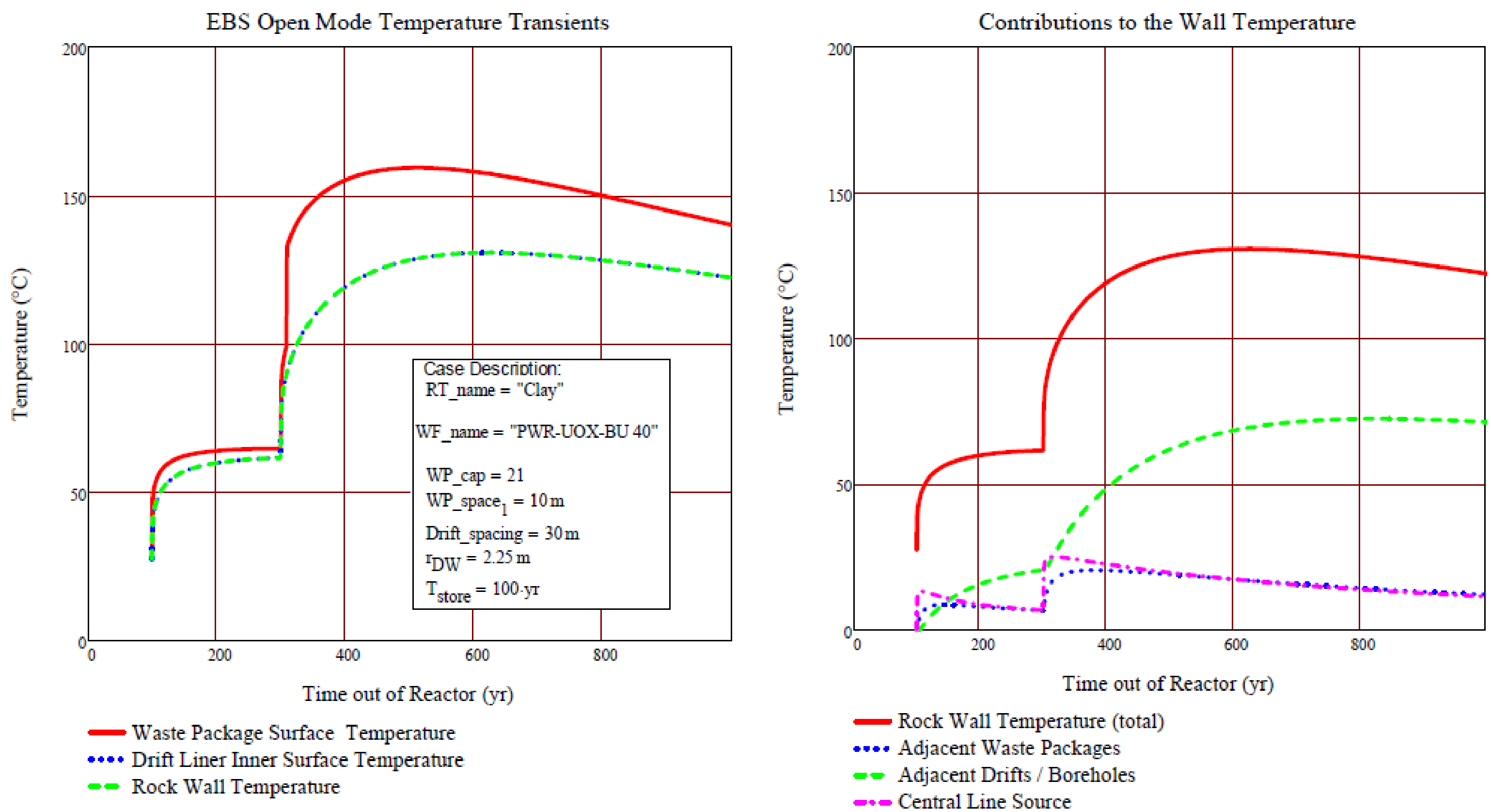


Figure B.2-10 Case 22 - Clay medium, 21-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

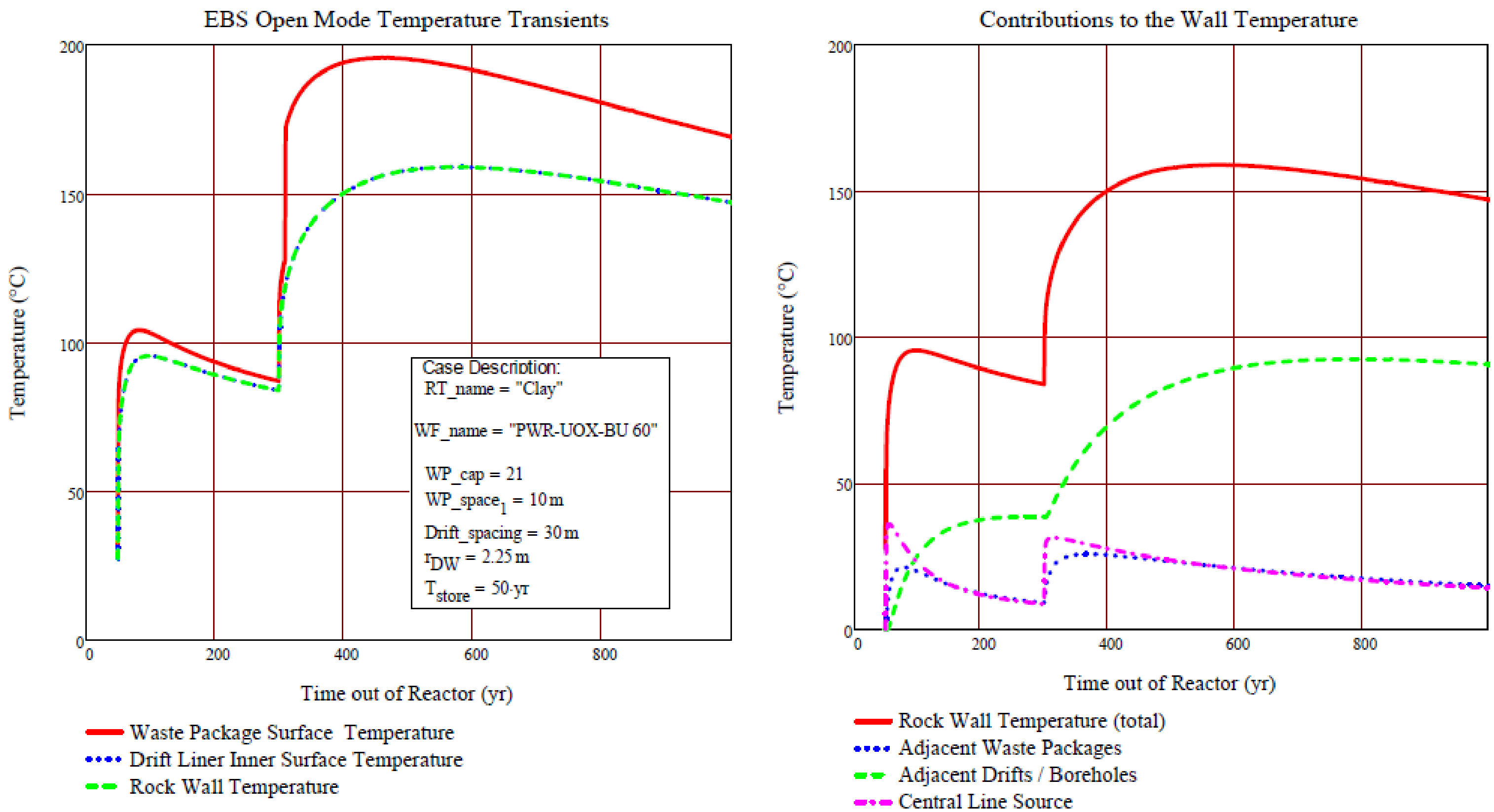


Figure B.2-11 Case 23 - Clay medium, 21-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

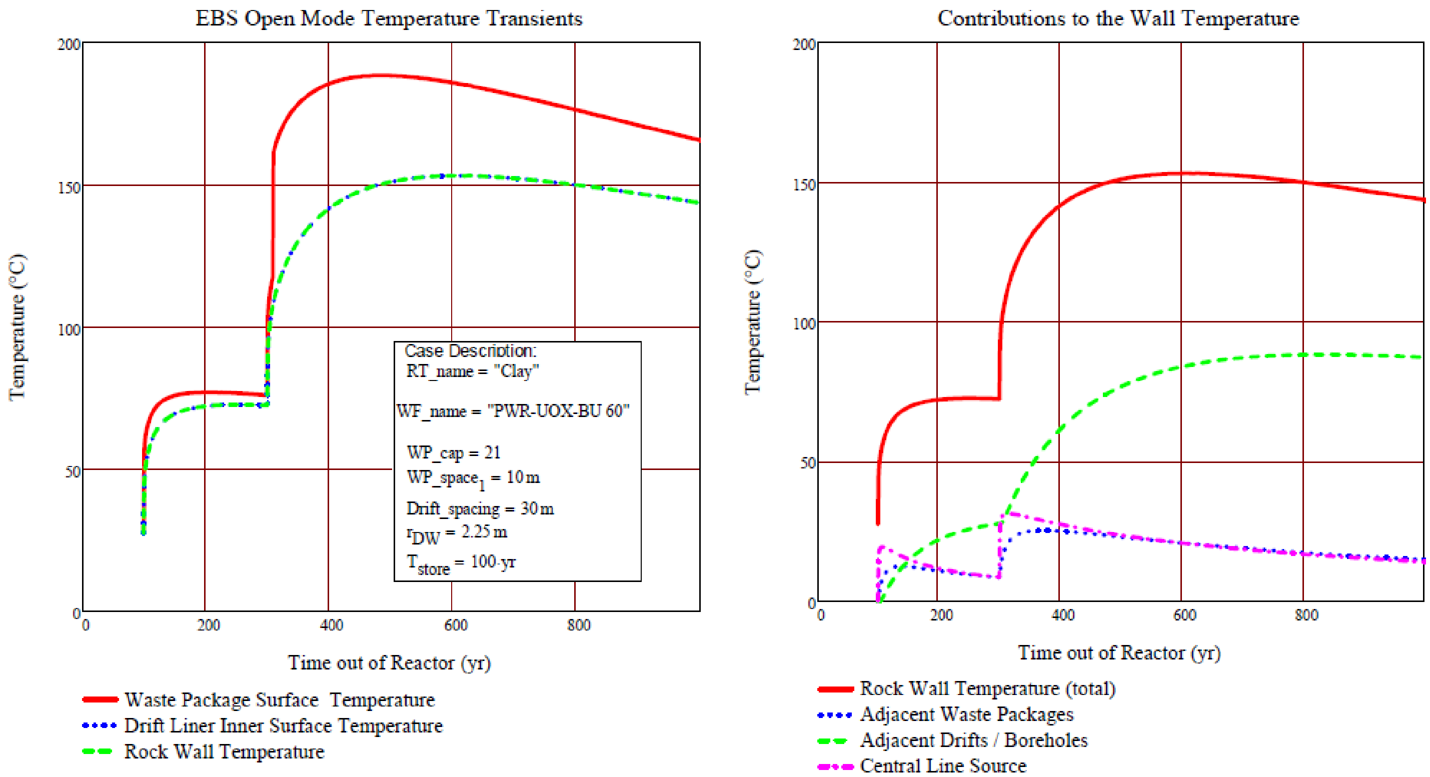


Figure B.2-12 Case 24 - Clay medium, 21-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

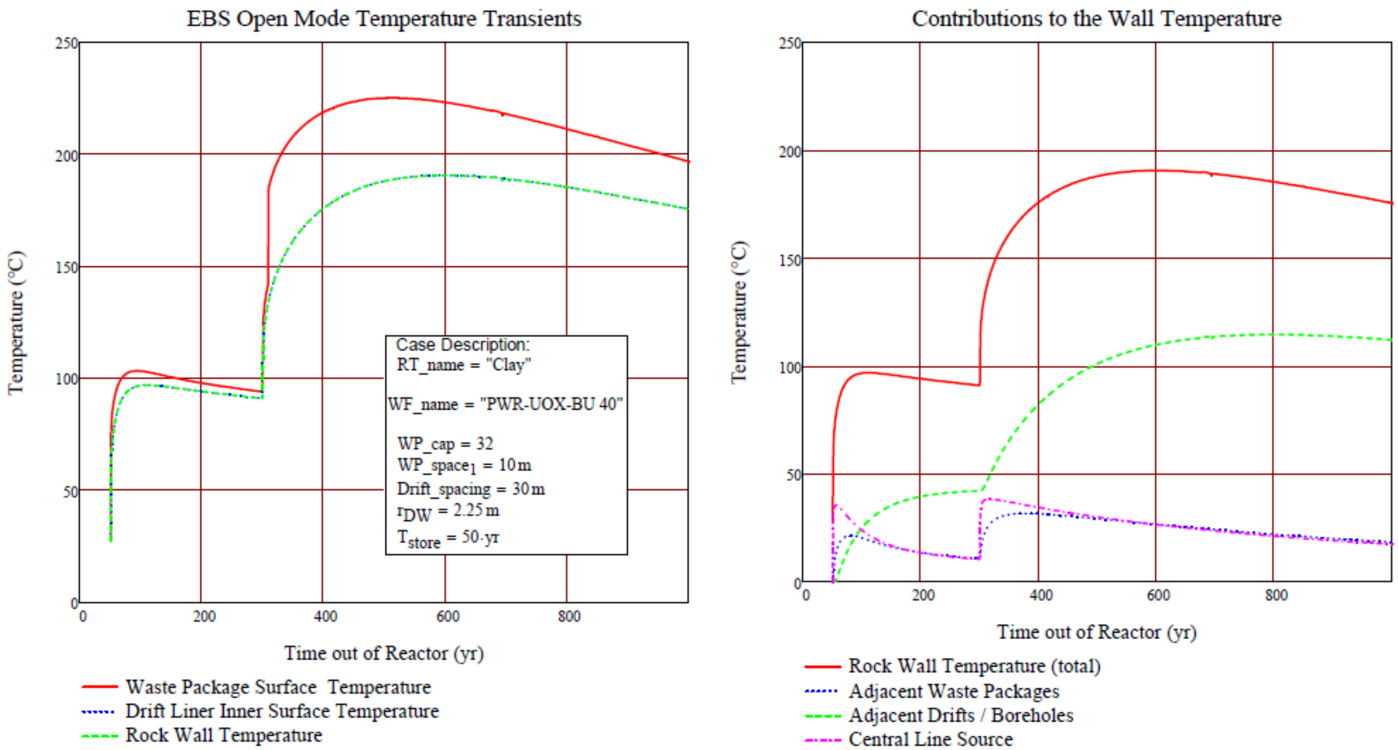


Figure B.2-13 Case 25 - Clay medium, 32-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 21 in Figure B.2-9. This is one of the base cases for the drift spacing sensitivity study in Appendix B.3.3.

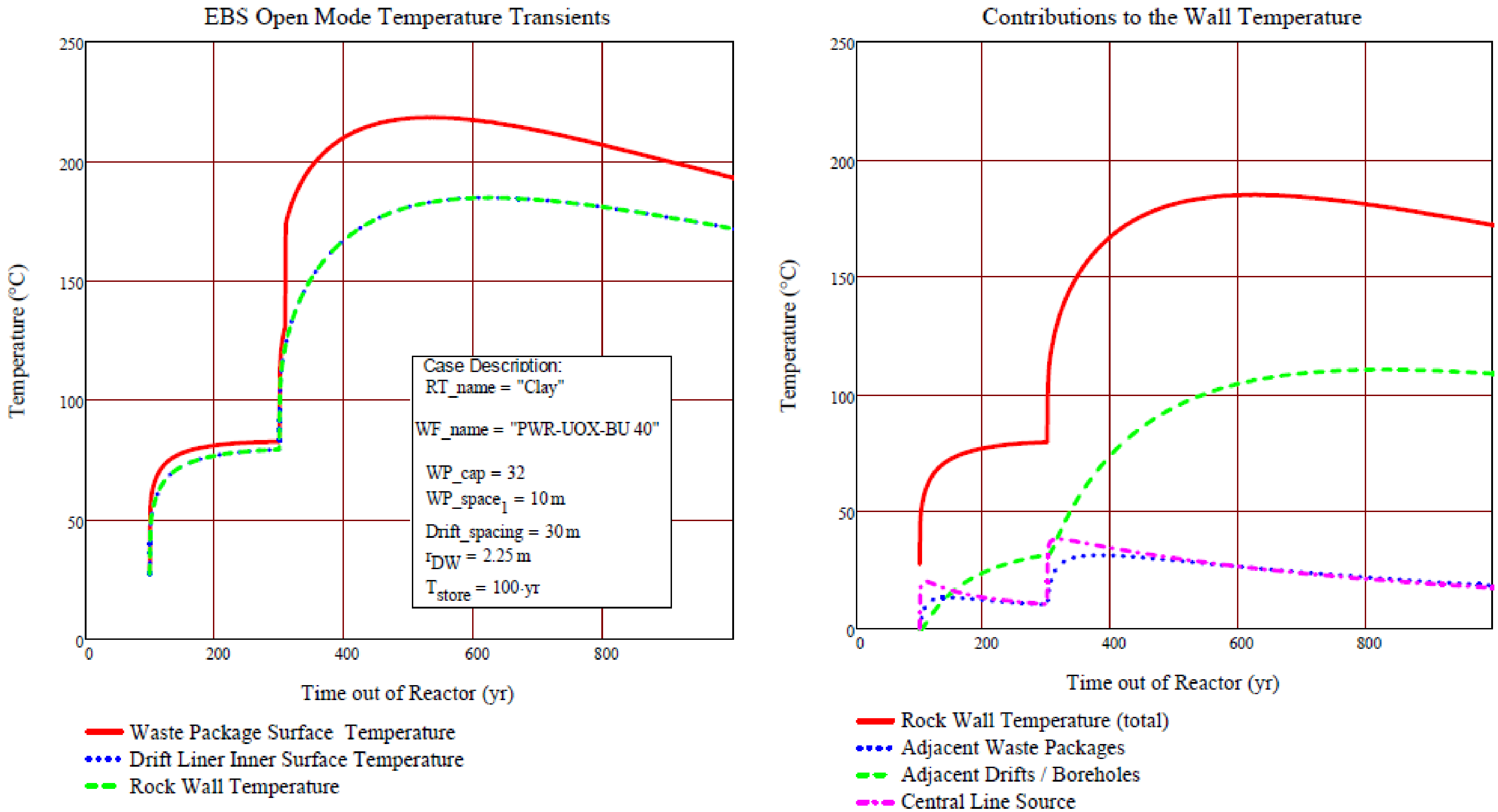


Figure B.2-14 Case 26 - Clay medium, 32-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

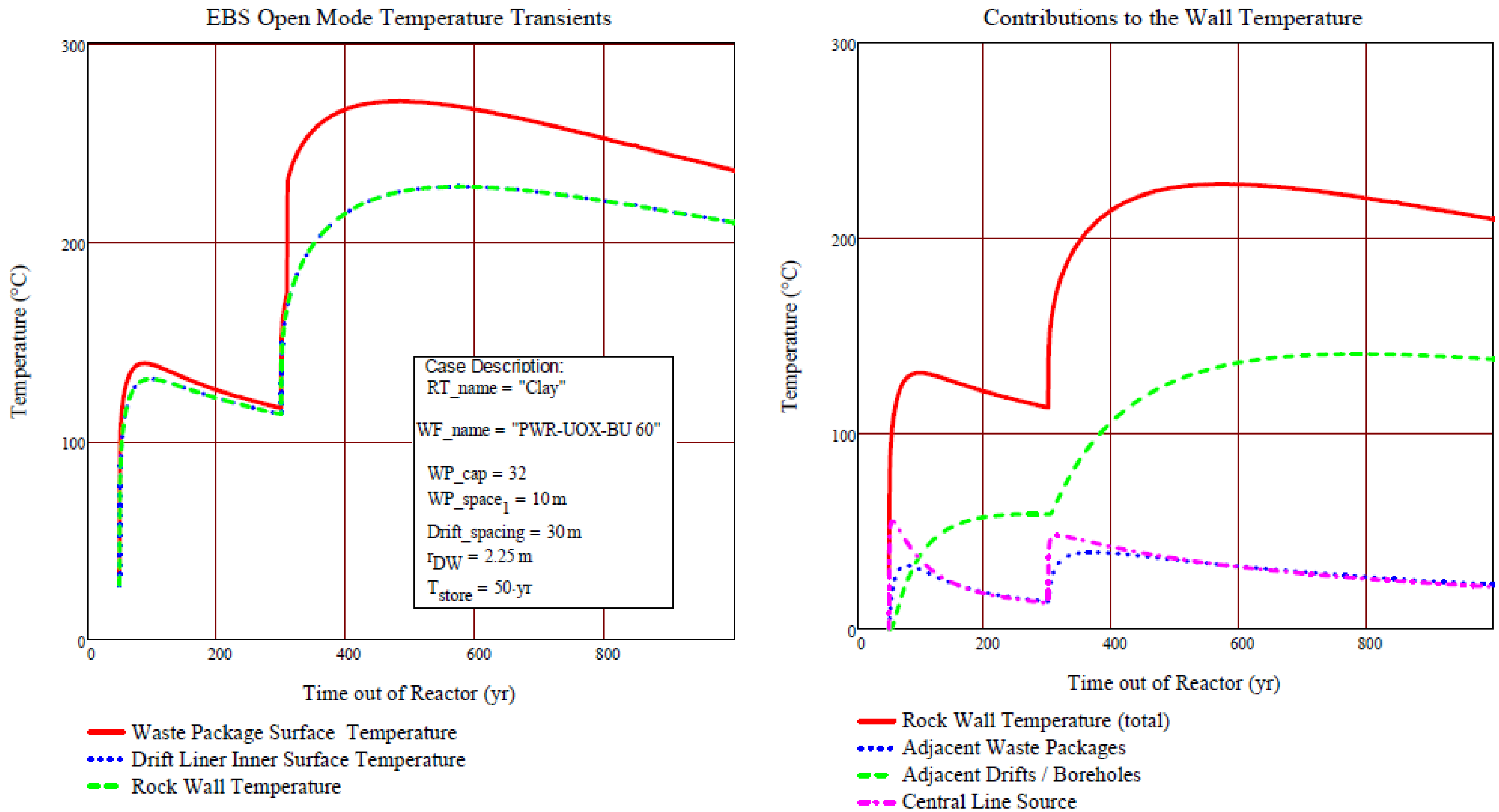


Figure B.2-15 Case 27- Clay medium, 32-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

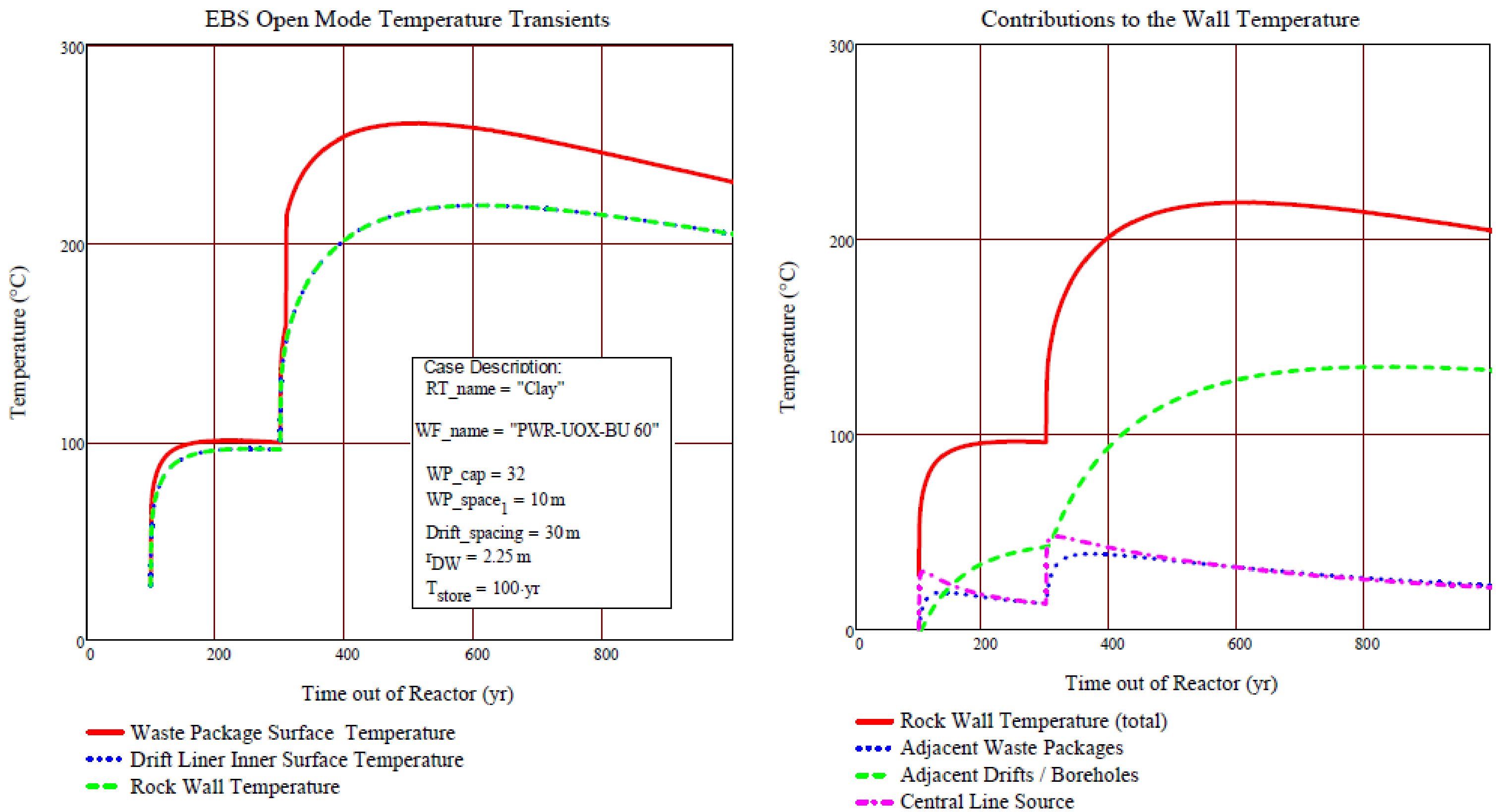


Figure B.2-16 Case 28 - Clay medium, 32-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 21 in Figure B.2-9.

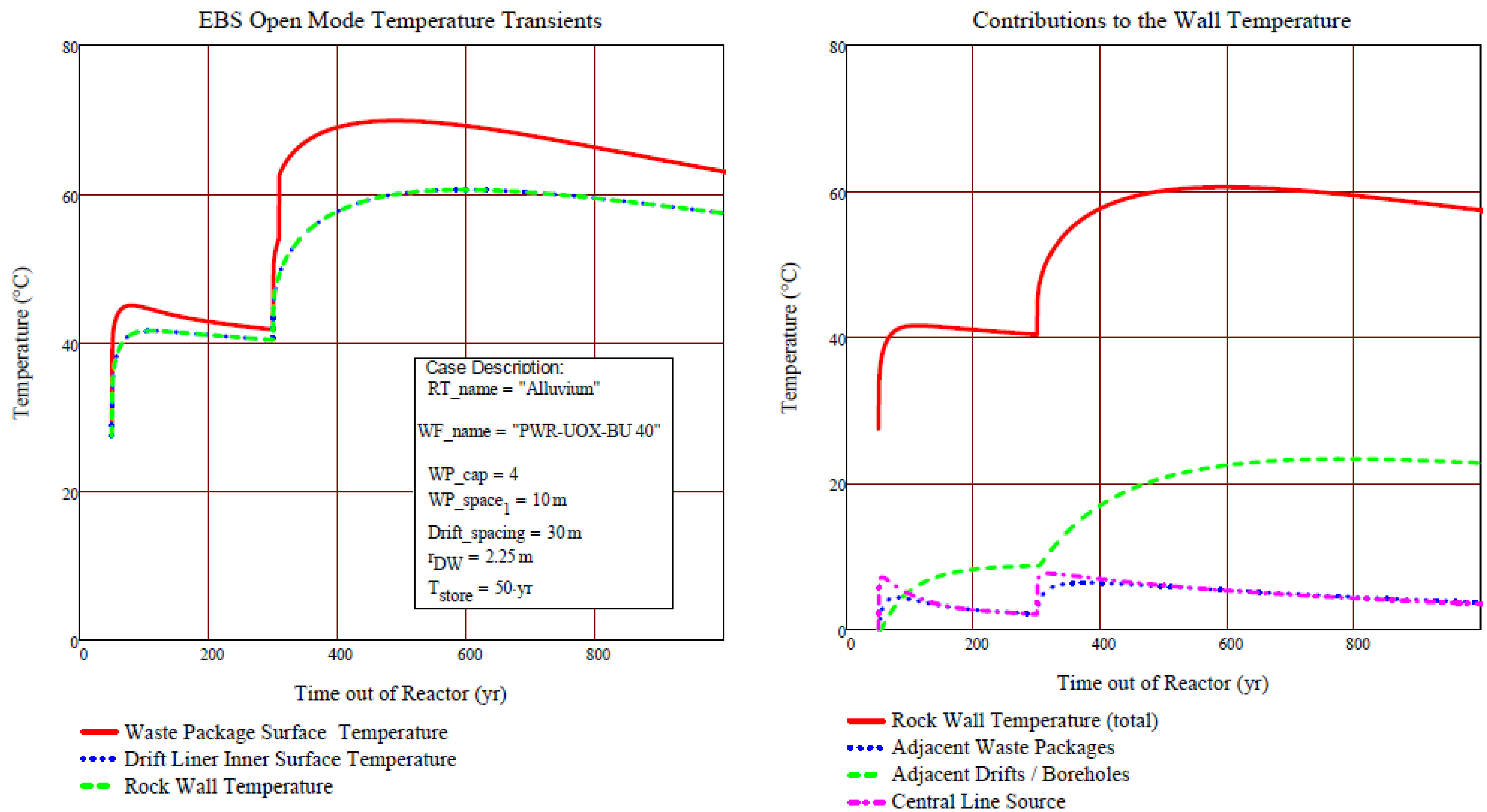


Figure B.2-17 Case 41 - Alluvium medium, 4-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

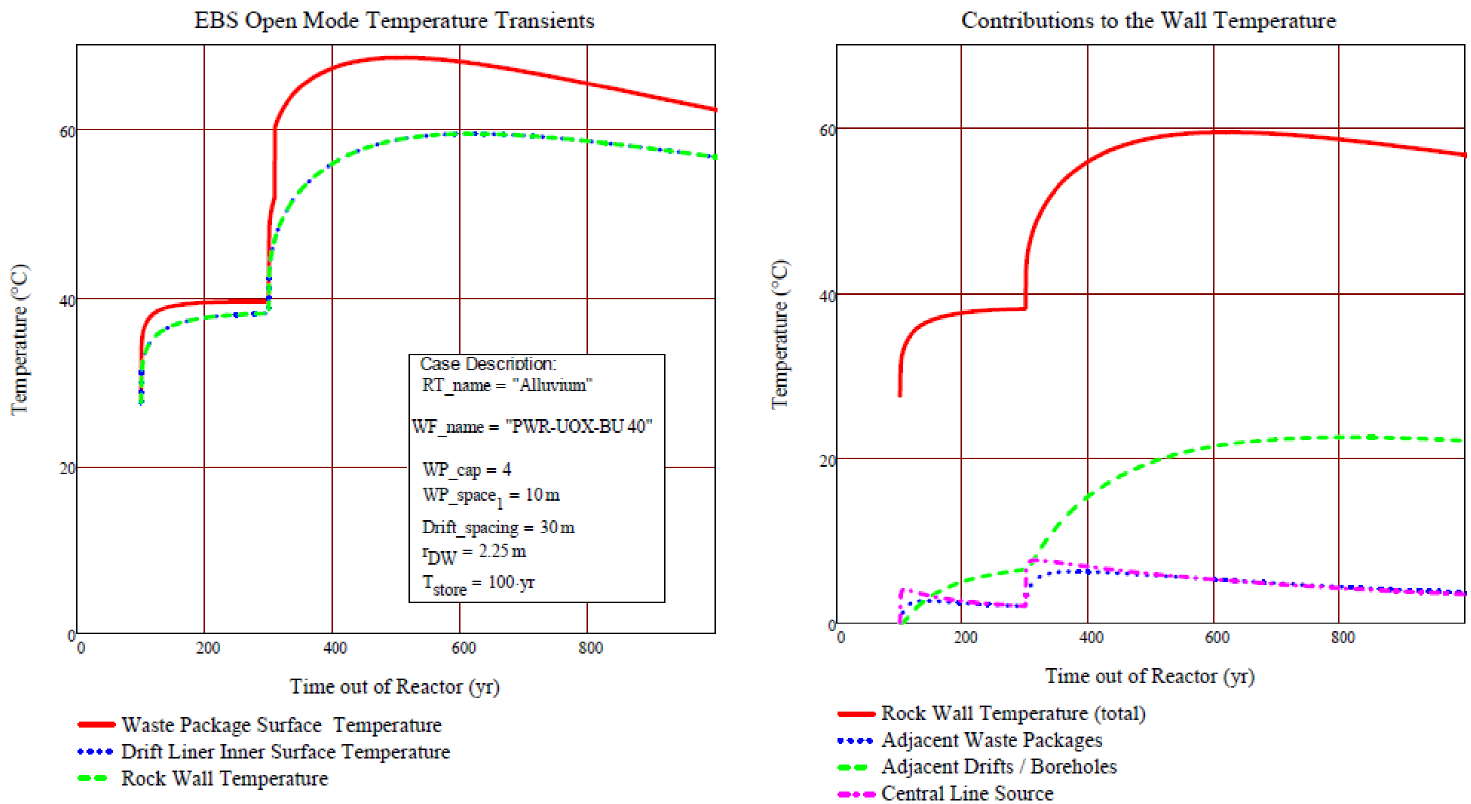


Figure B.2-18 Case 42 - Alluvium medium, 4-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

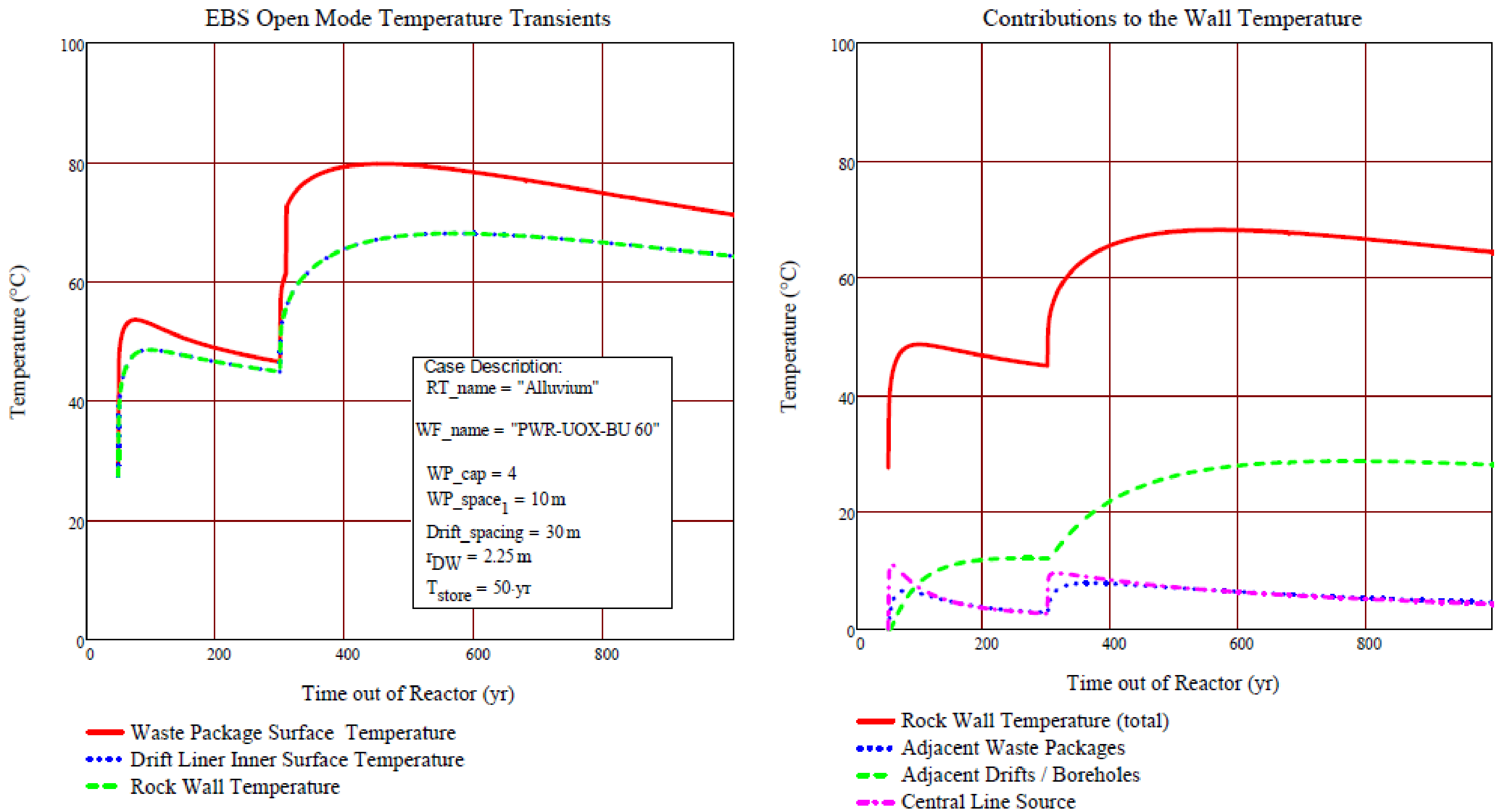


Figure B.2-19 Case 43 - Alluvium medium, 4-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

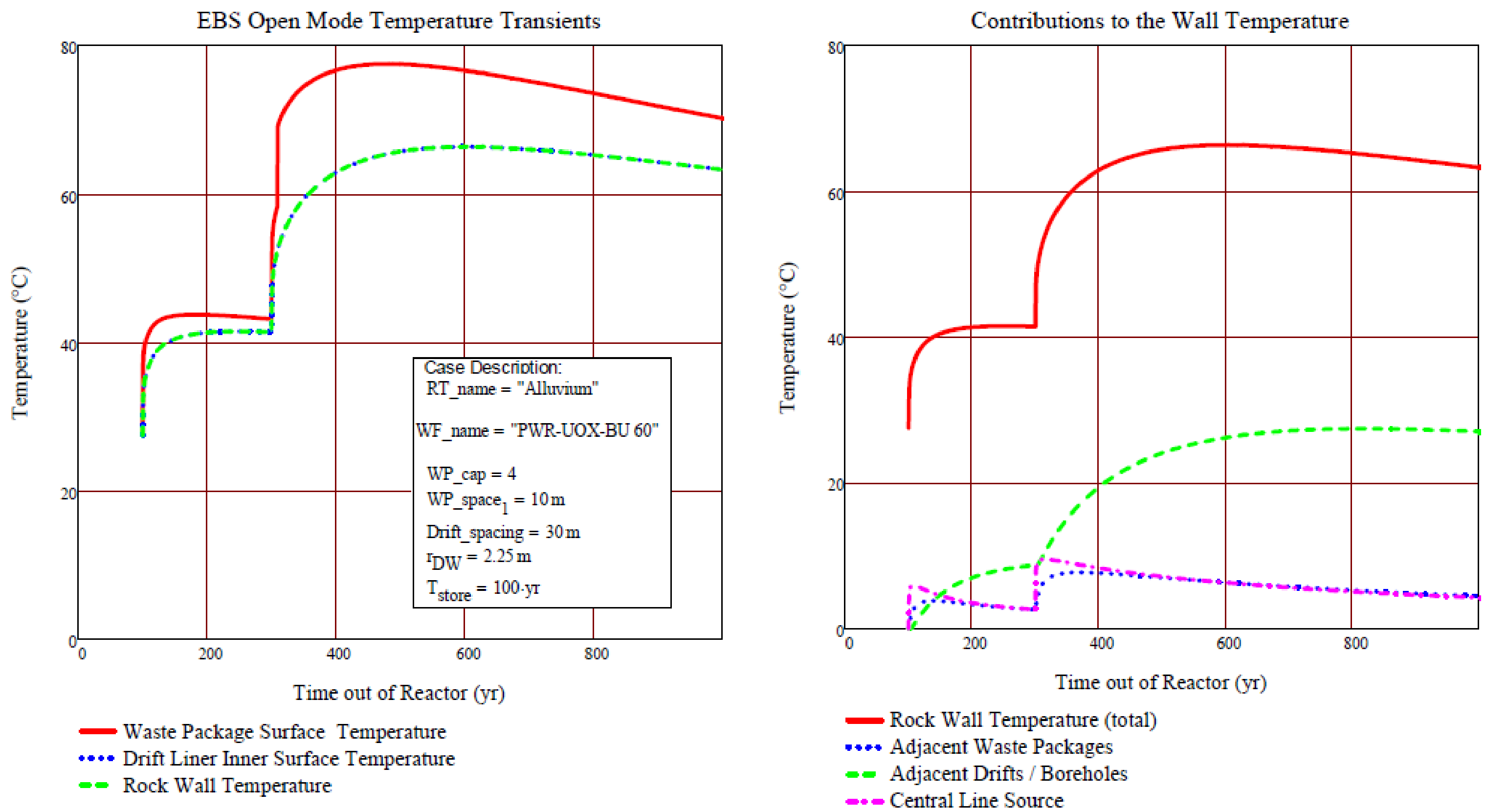


Figure B.2-20 Case 44 - Alluvium medium, 4-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

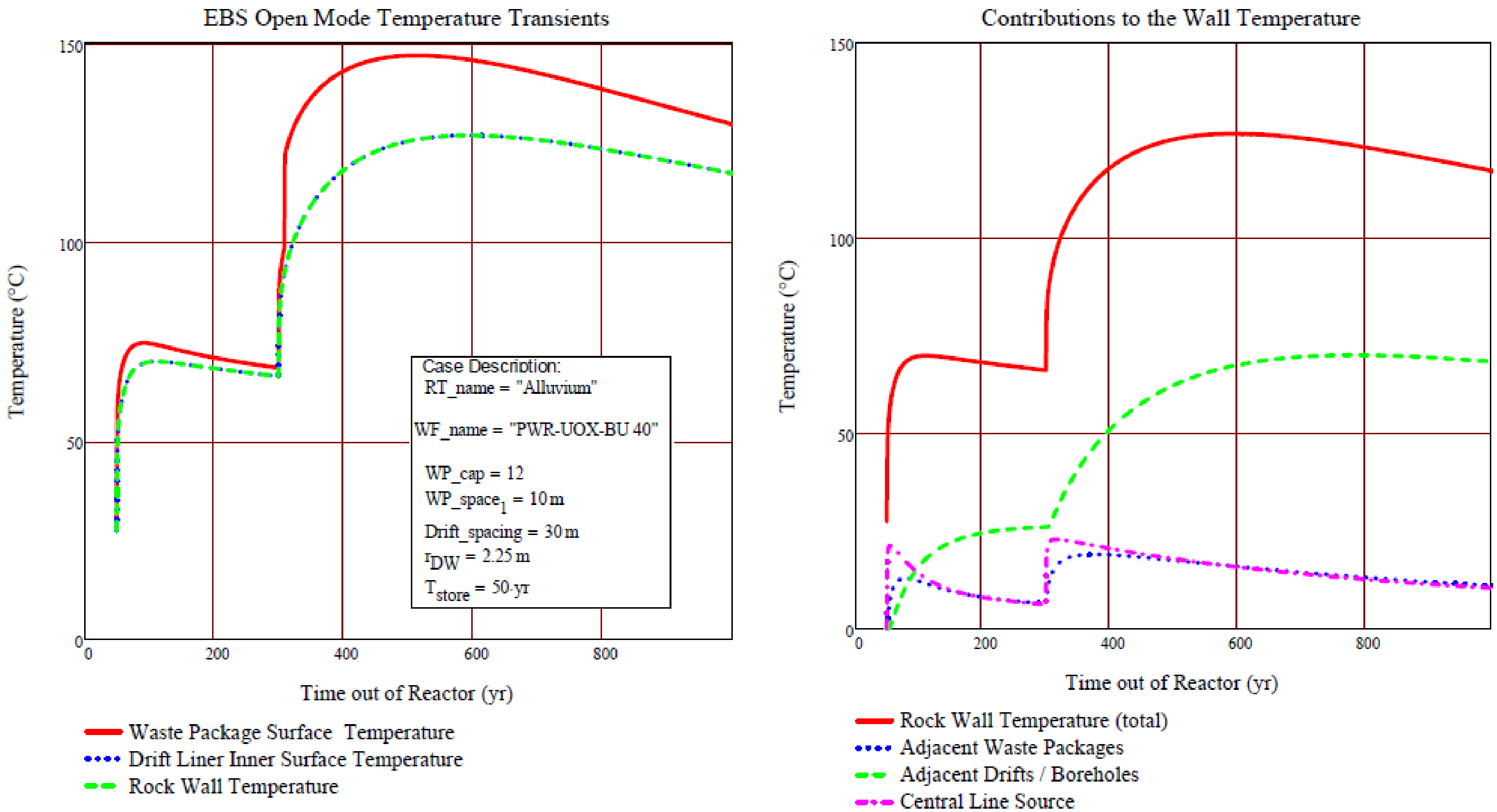


Figure B.2-21 Case 45 - Alluvium medium, 12-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

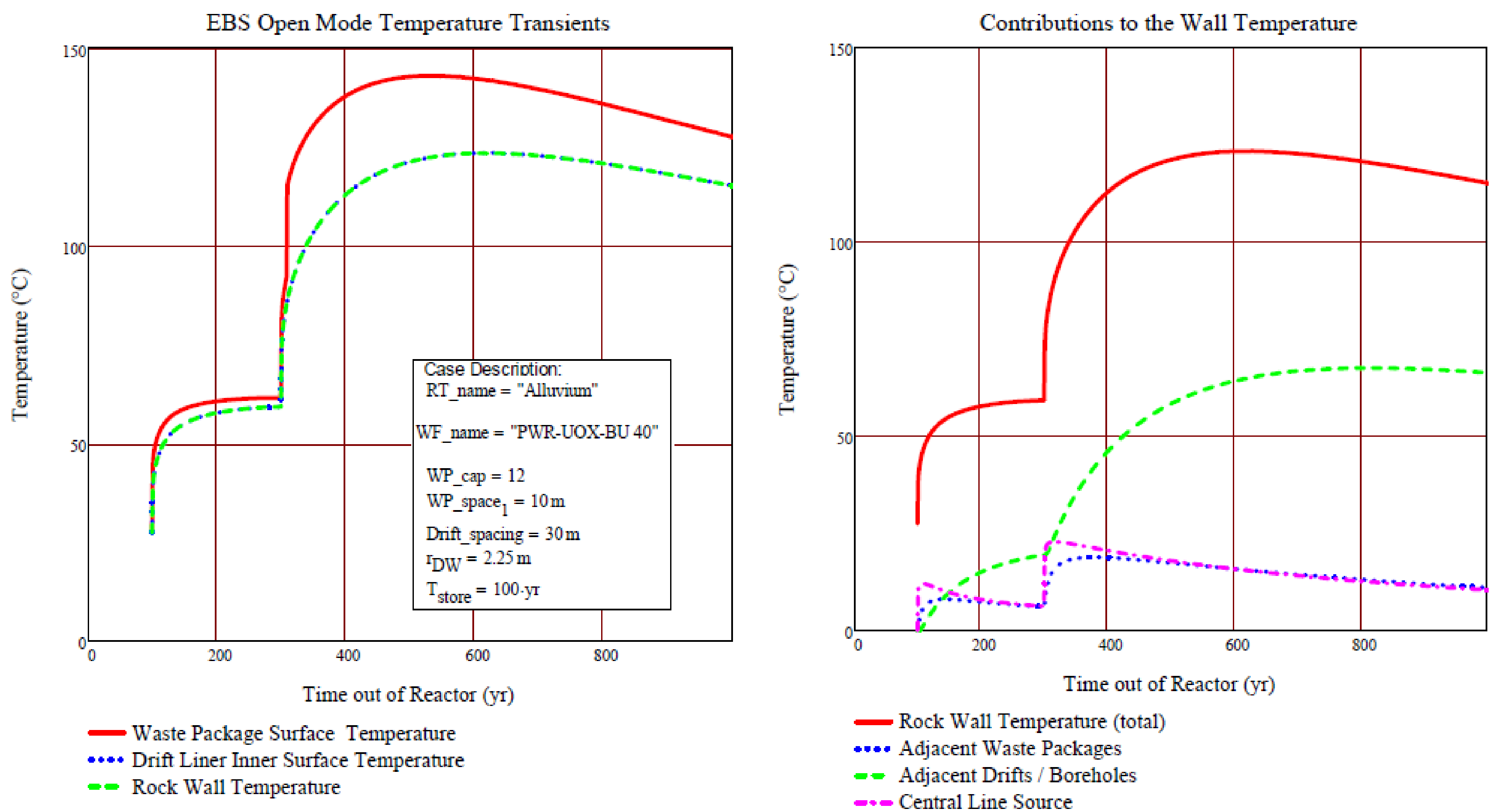


Figure B.2-22 Case 46 - Alluvium medium, 12-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr. For other parameters, see Base Case 49 in Figure B.2-25.

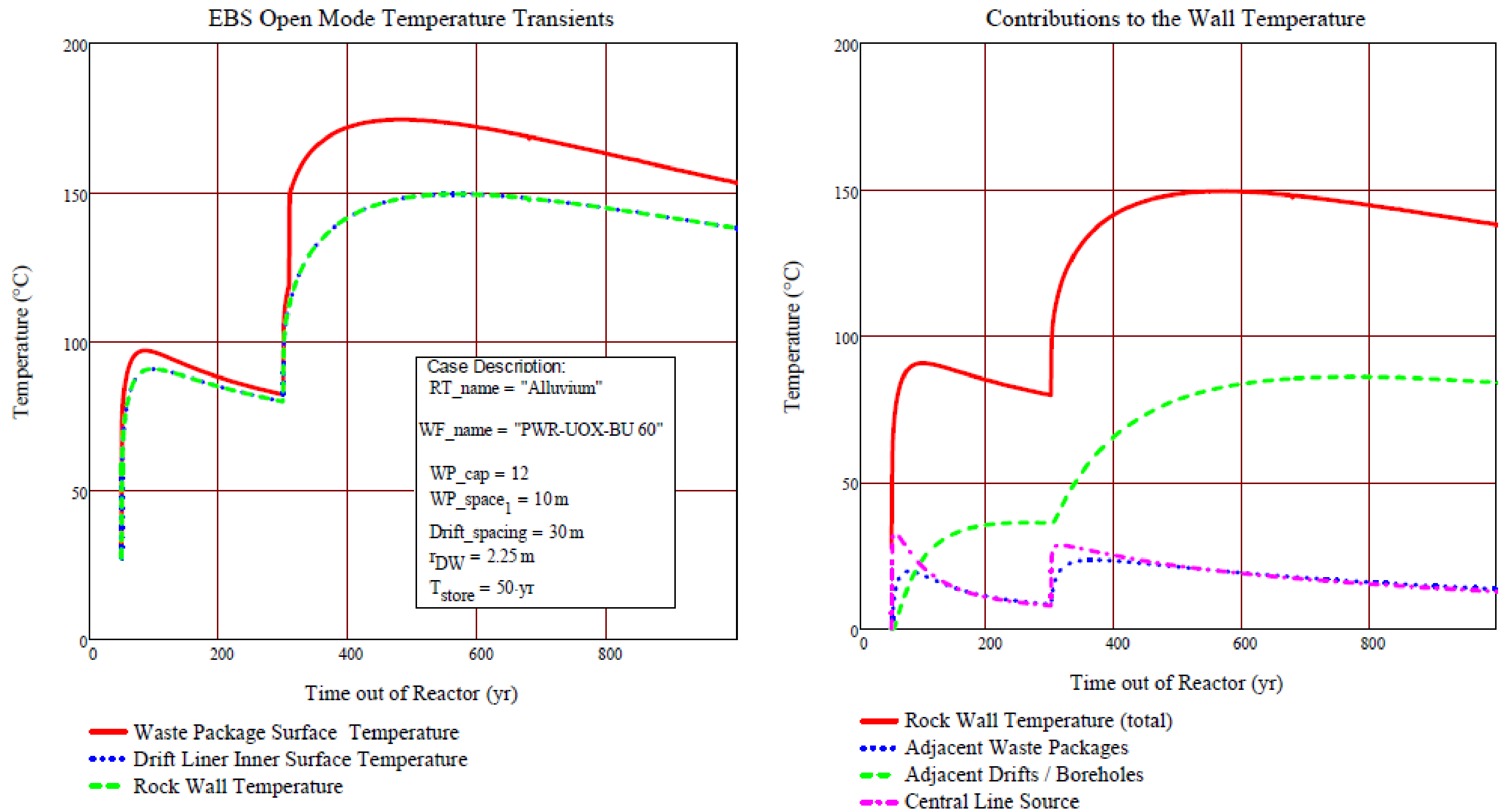
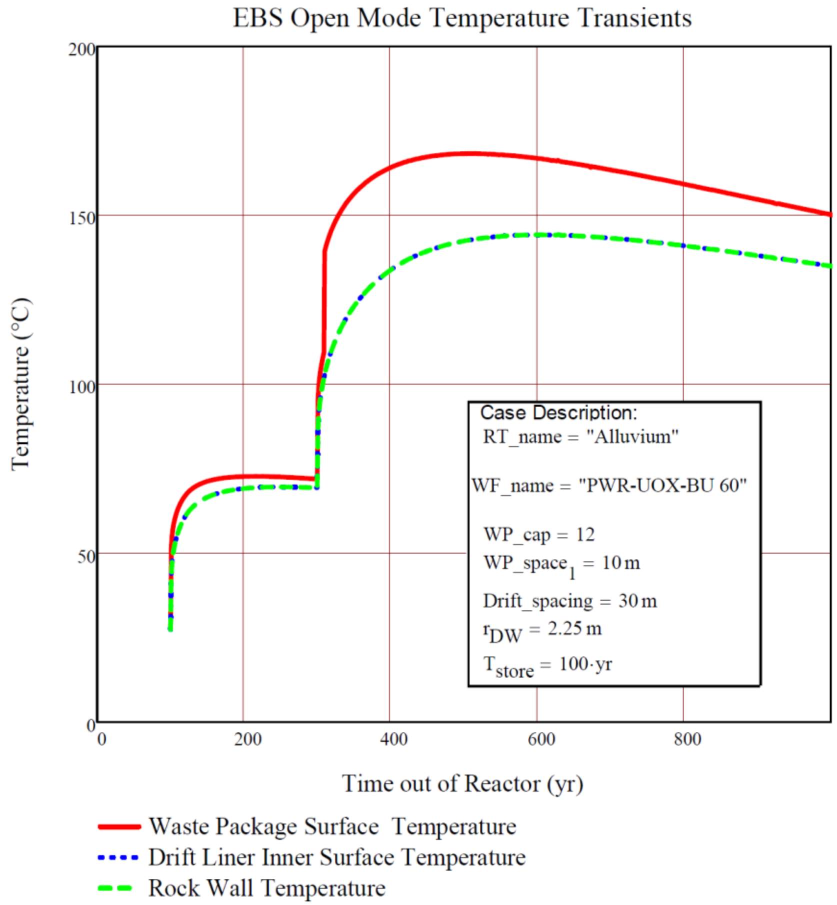


Figure B.2-23 Case 47 - Alluvium medium, 12-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr. For other parameters, see Base Case 49 in Figure B.2-25.



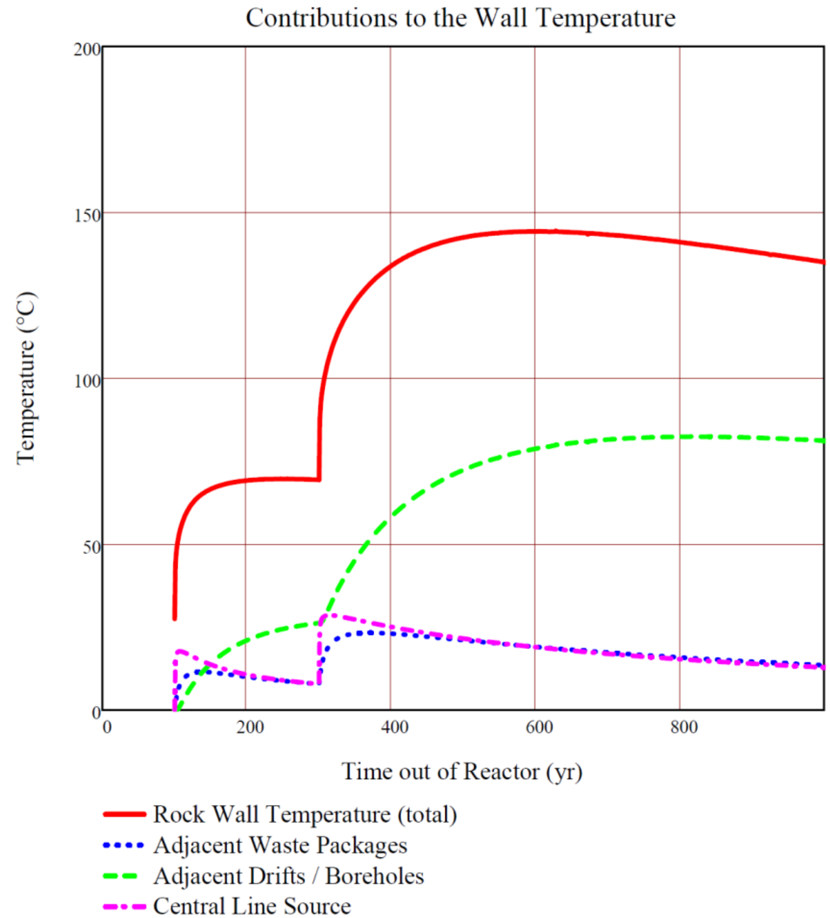


Figure B.2-24 Case 48 - Alluvium medium, 12-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

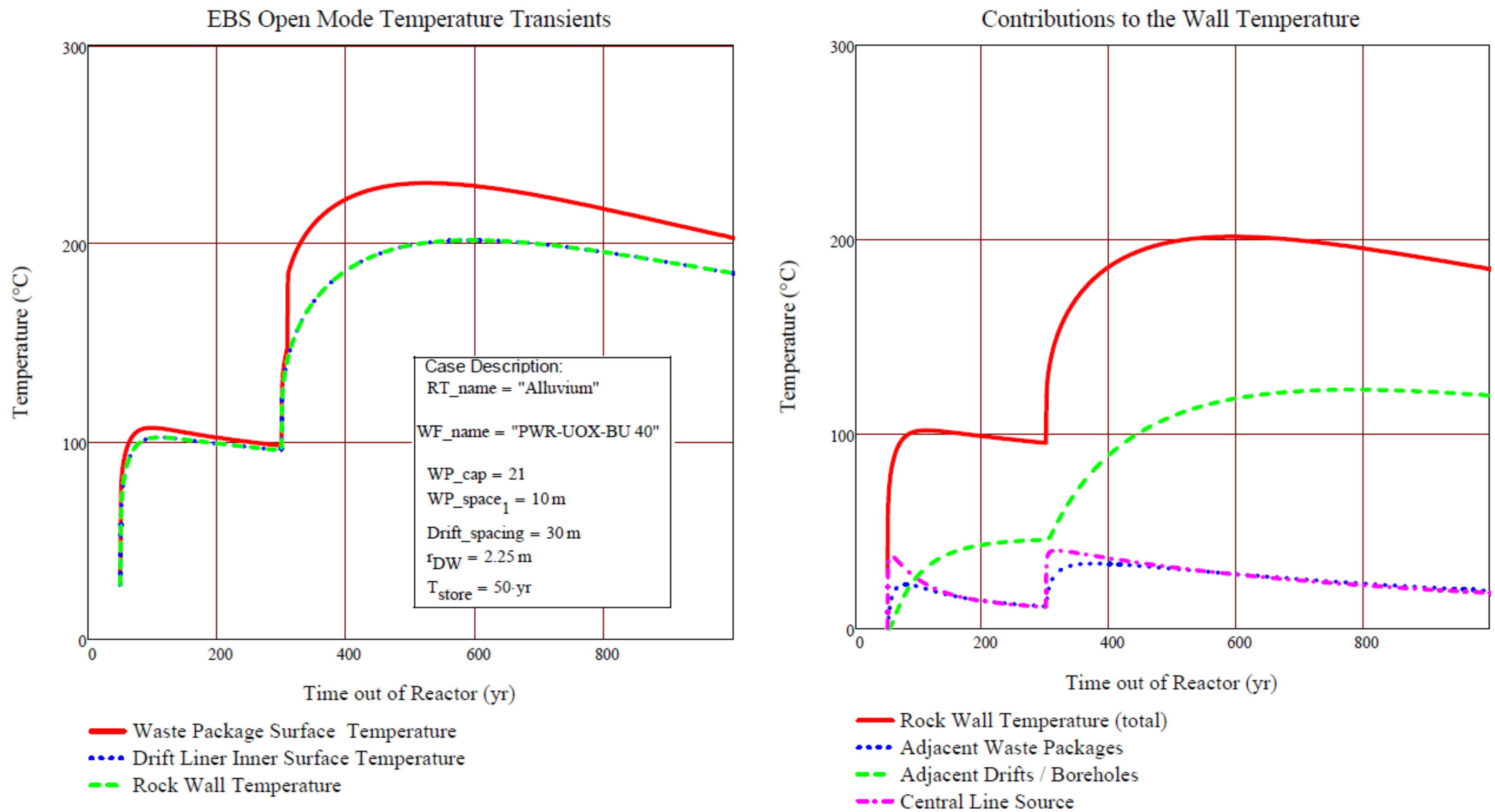
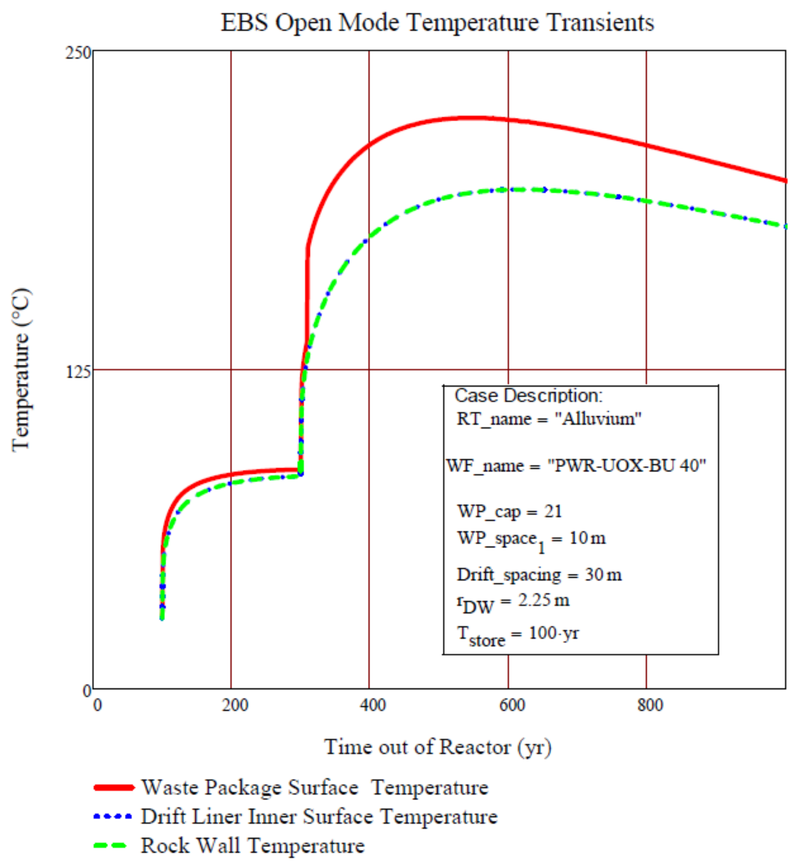


Figure B.2-25 Case 49 - Alluvium medium, 21-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr.

This is one base case for this Appendix B.2 and is also the base case for the uncertainty analysis in Appendix B.4.



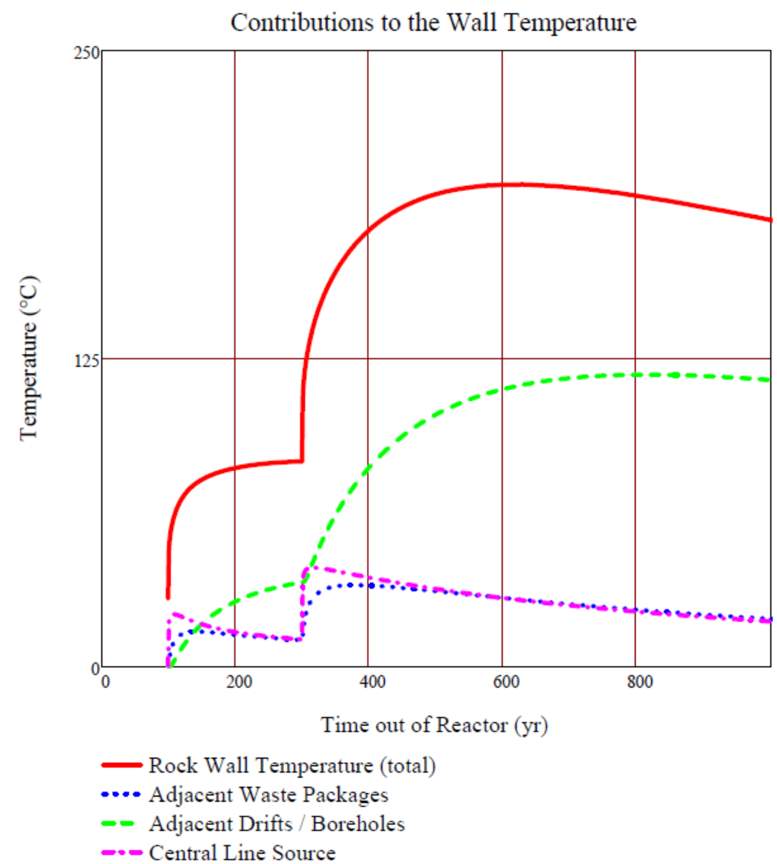
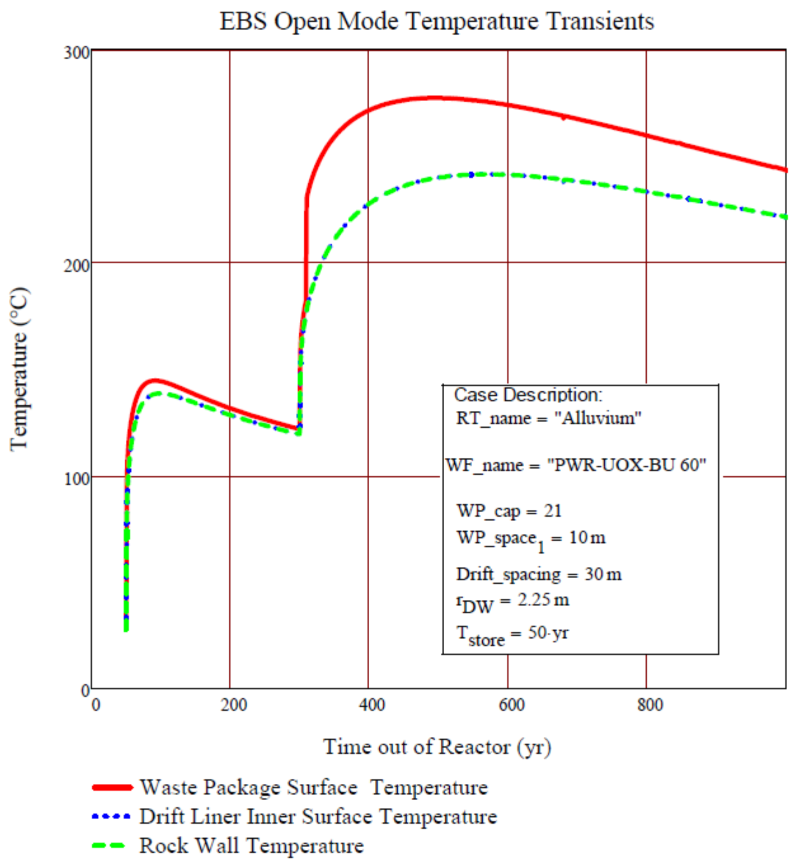


Figure B.2-26 Case 50 - Alluvium medium, 21-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-25.



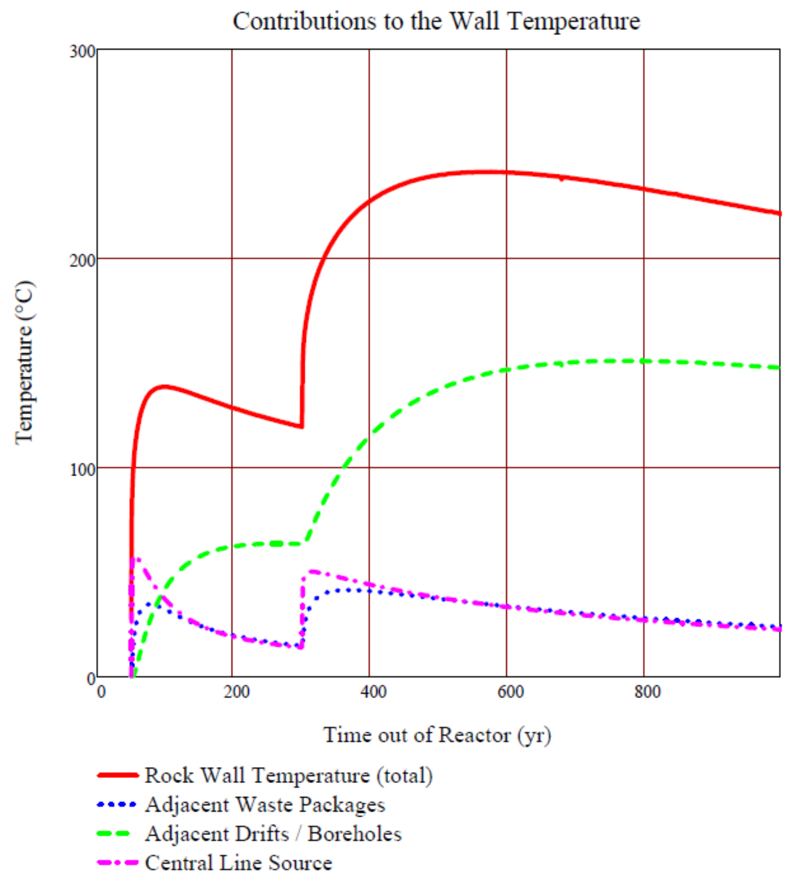


Figure B.2-27 Case 51 - Alluvium medium, 21-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

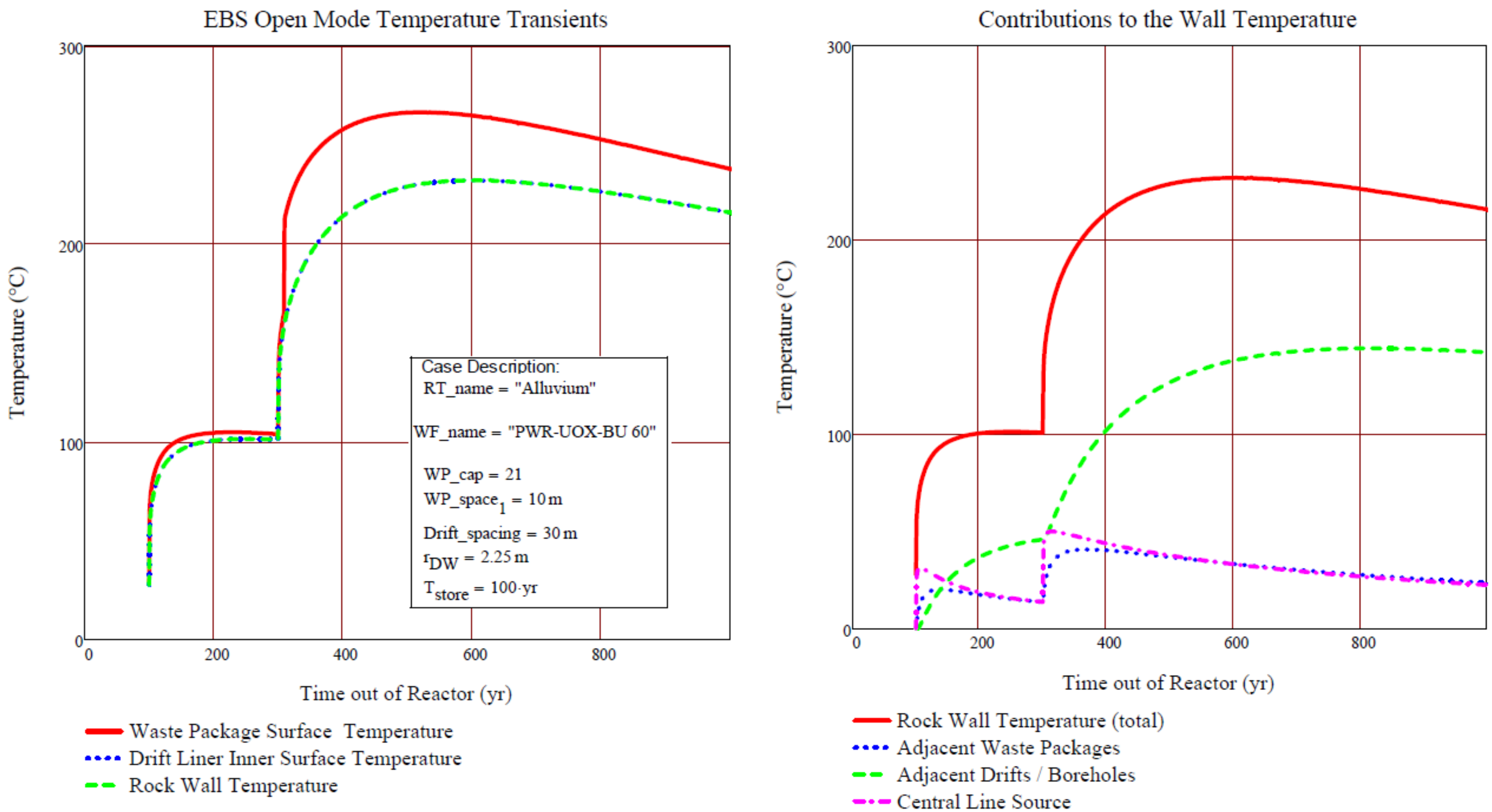


Figure B.2-28 Case 52 - Alluvium medium, 21-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-2

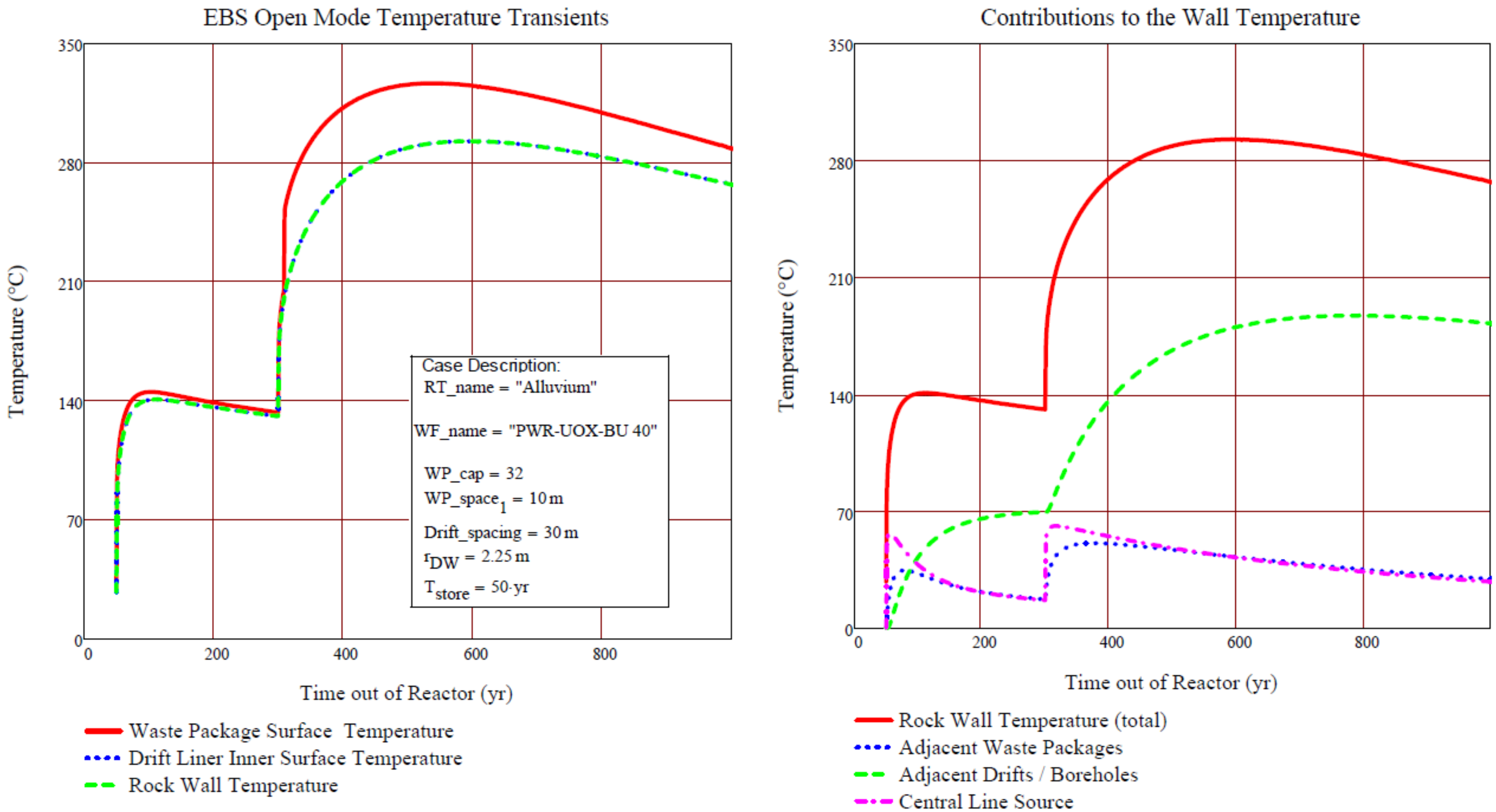


Figure B.2-29 Case 53 - Alluvium medium, 32-UOX WPs with 40 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

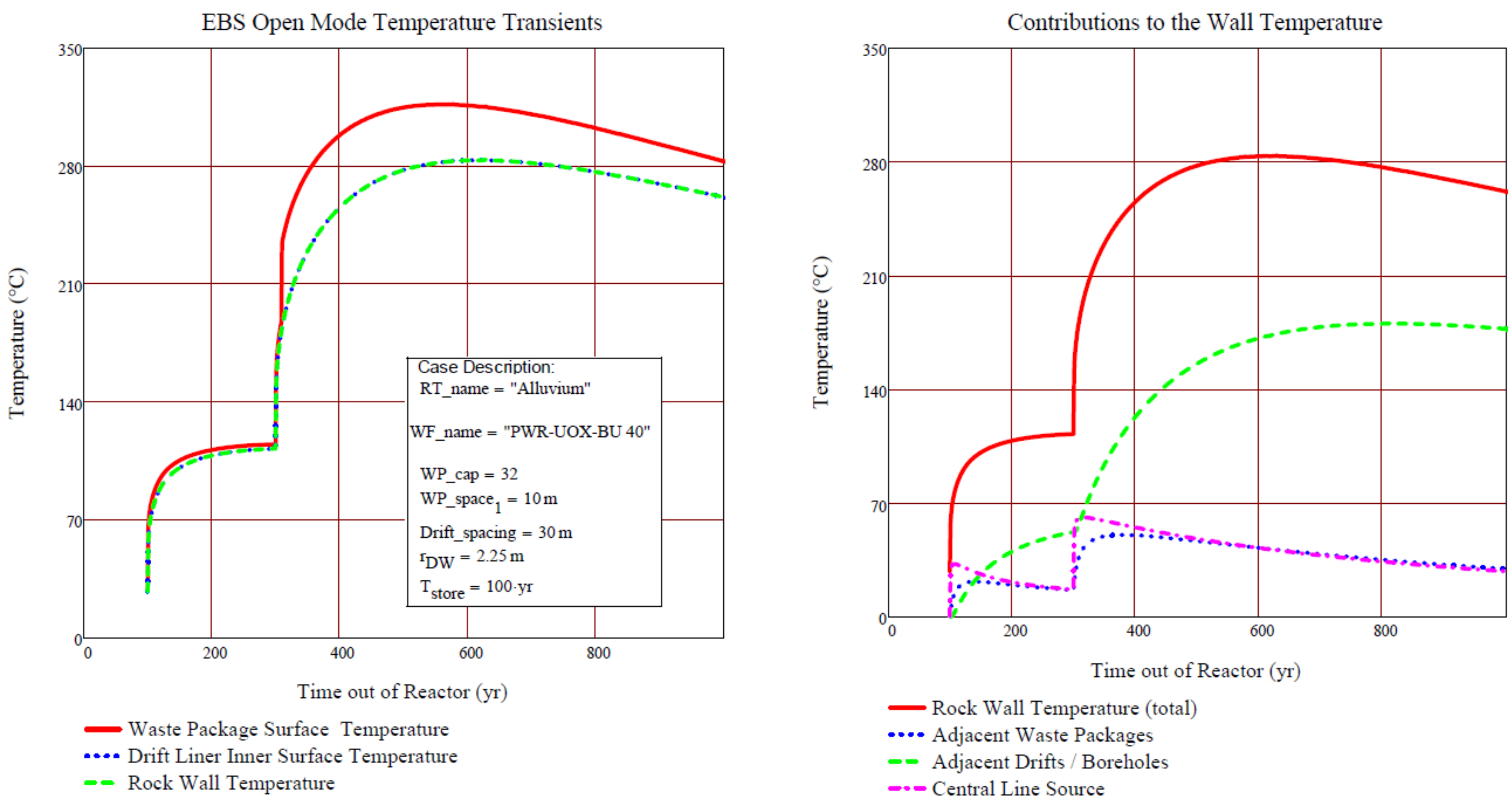


Figure B.2-30 Case 54 - Alluvium medium, 32-UOX WPs with 40 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

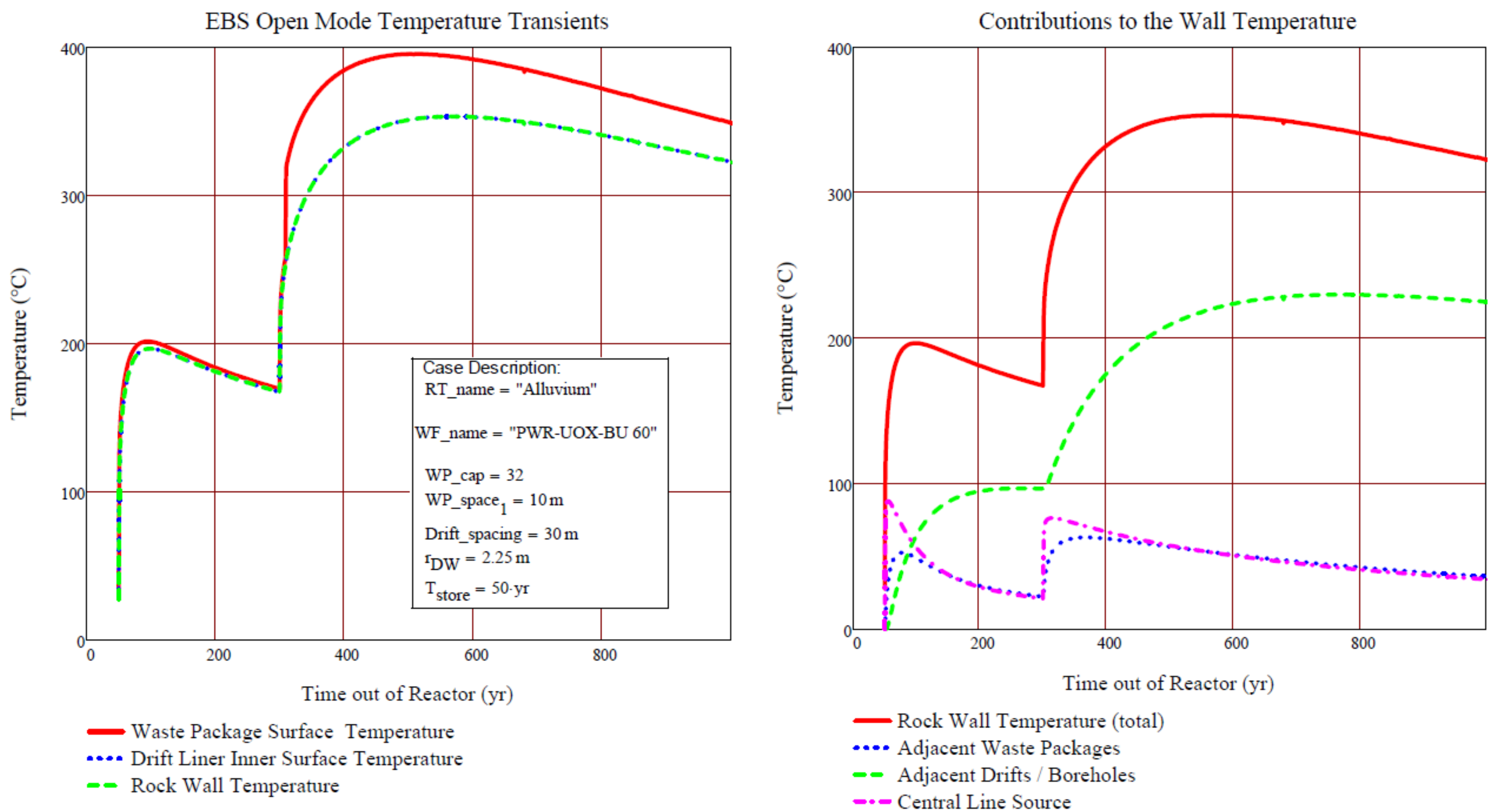


Figure B.2-31 Case 55 - Alluvium medium, 32-UOX WPs with 60 GWd/MT burnup, and storage time of 50 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

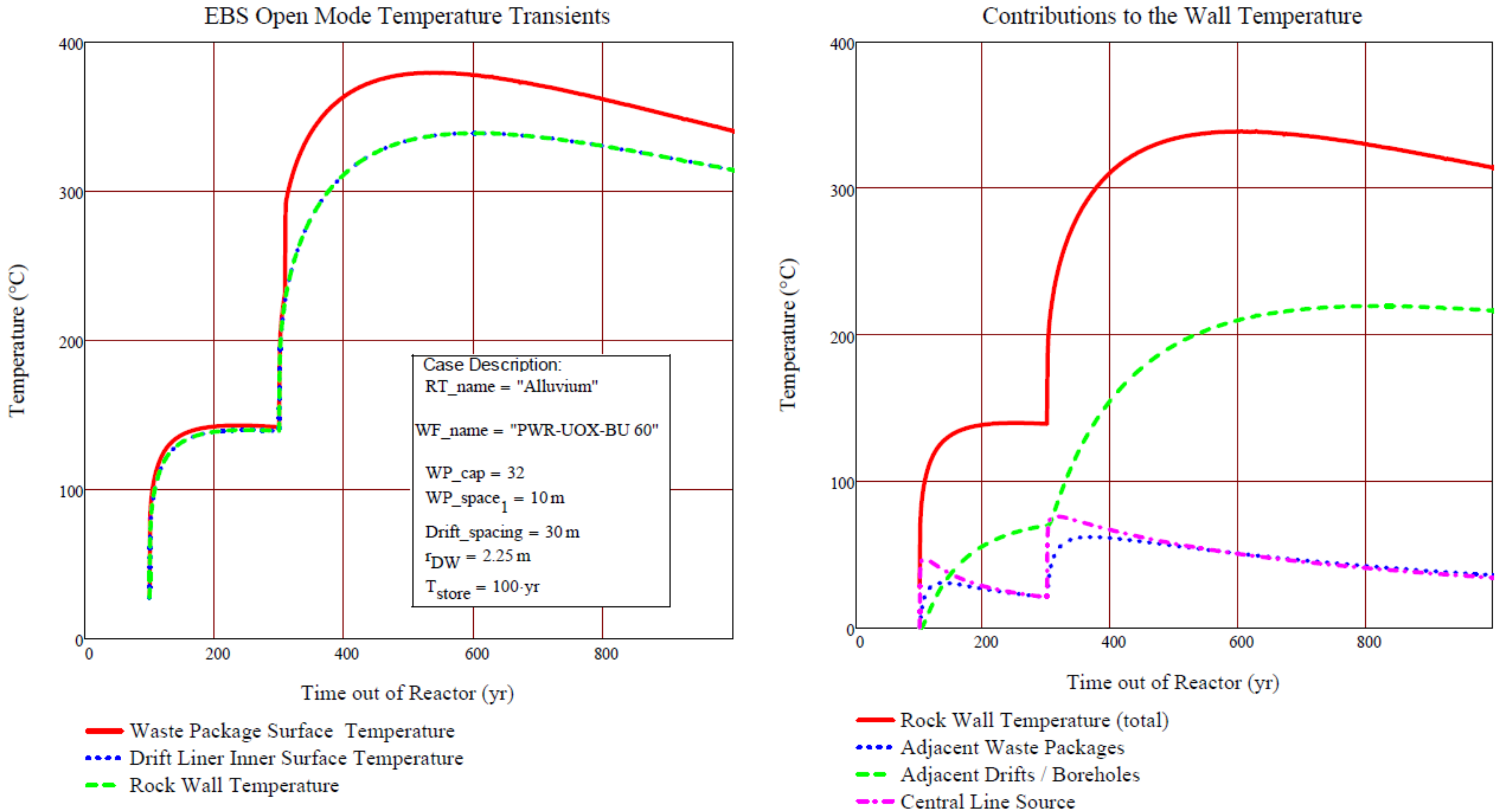


Figure B.2-32 Case 56 - Alluvium medium, 32-UOX WPs with 60 GWd/MT burnup, and storage time of 100 yr.

For other parameters, see Base Case 49 in Figure B.2-25.

B.3 SENSITIVITY ANALYSES

This appendix documents sensitivity calculations for ventilation efficiency (B.3.1), ventilation operational period (B.3.2), drift/borehole (lateral) spacing (B.3.3), and rock thermal conductivity (B.3.4)

B.3.1 SENSITIVITY TO VENTILATION SYSTEM THERMAL EFFICIENCY

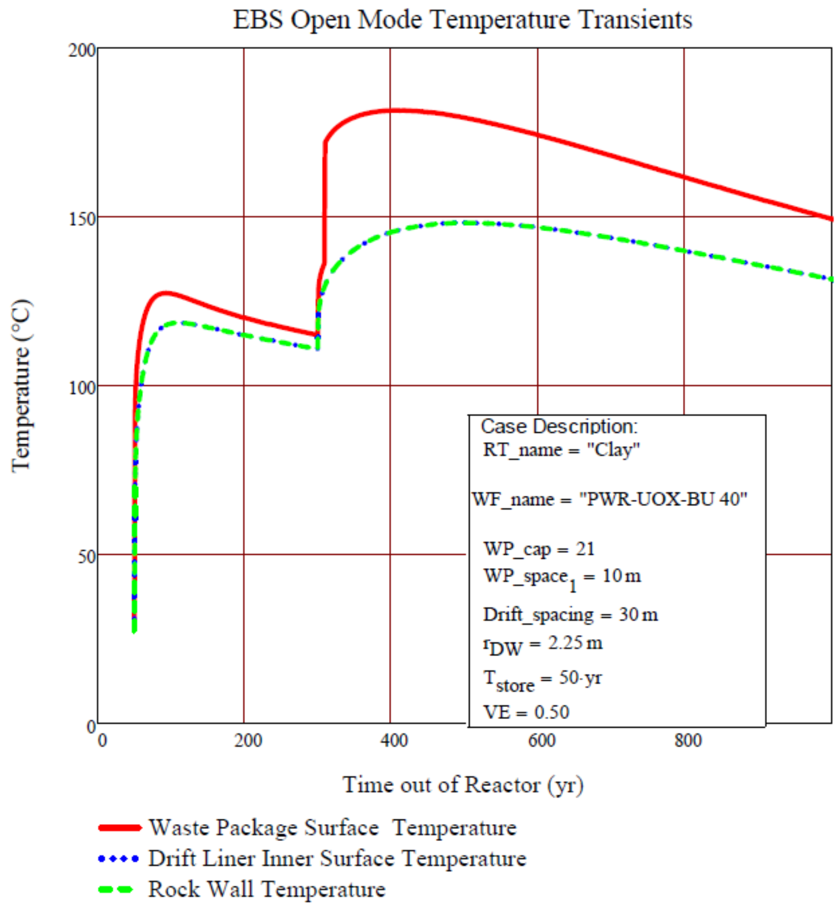
Table B.3-1 List of cases used in the ventilation efficiency sensitivity study for clay

Assumes 50 yr of storage, 250 yr of ventilation, and 10 year of backfill emplacement. WPs are 21-UOX with 40 GWd/MT burnup. Axial spacing is 10 m, and lateral (drift/borehole) spacing is 30 m.

Figure Number	Case Number	Ventilation Thermal Efficiency		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-1	21a	50%		148.2	491		181.5	410
B.3-2	21b	60%		142.7	545		174.0	442
B.3-3	21c	70%		137.1	567		167.2	468
B.3-4	**21**	**75%**		134.6	593		164.1	488
B.3-5	21d	80%		132.2	608		161.0	516
B.3-6	**21e**	**90%**		127.6	659		155.2	539

The base case (21) has 75% ventilation efficiency. All cases have 50 yr of storage, 250 yr of ventilation, and 10 yr of backfill emplacement. WPs are 21-UOX with 40 GWd/MT burnup. The geologic medium is clay. Axial spacing is 10 m, and lateral (drift/borehole) spacing is 30 m for all the cases.

Case 21 is also used in Appendix B.2. Case 21e is the base case for the sensitivity study in Appendix B.3.2.



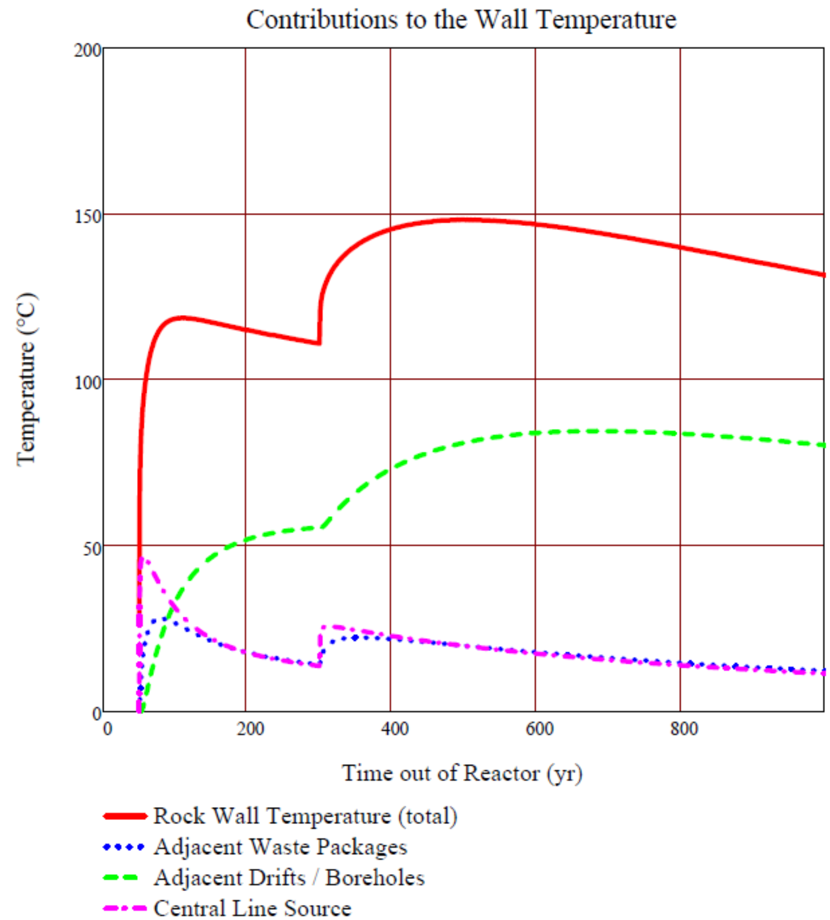
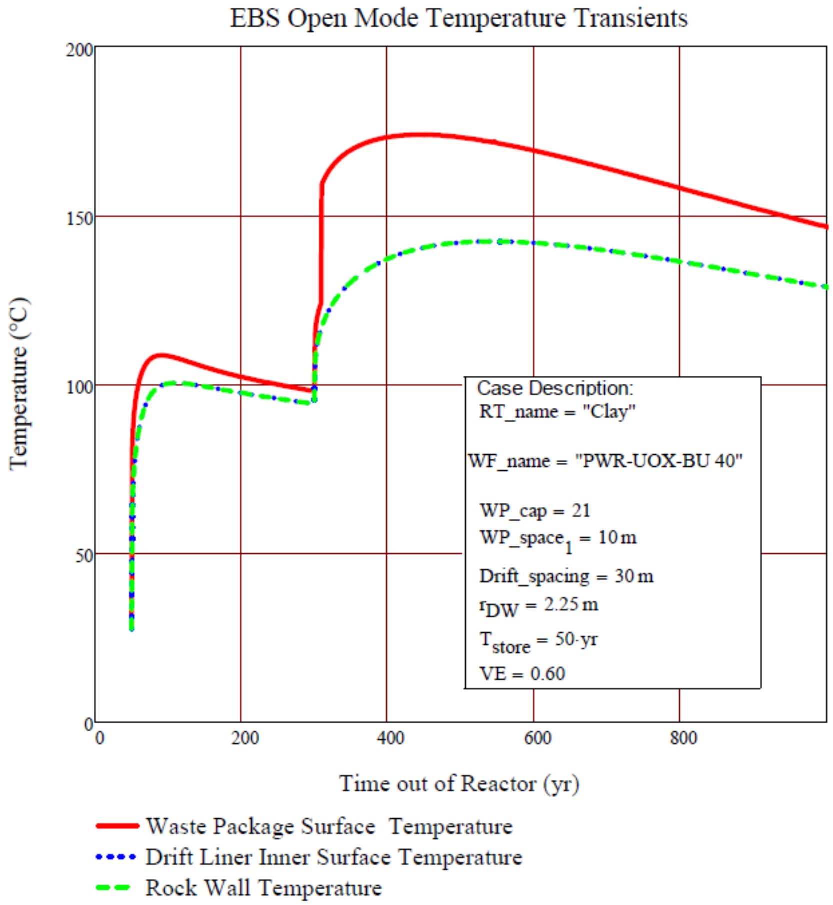


Figure B.3-1 Case 21a – 50% Ventilation efficiency.

See Base Case 21, Figure B.3-4, for case parameters



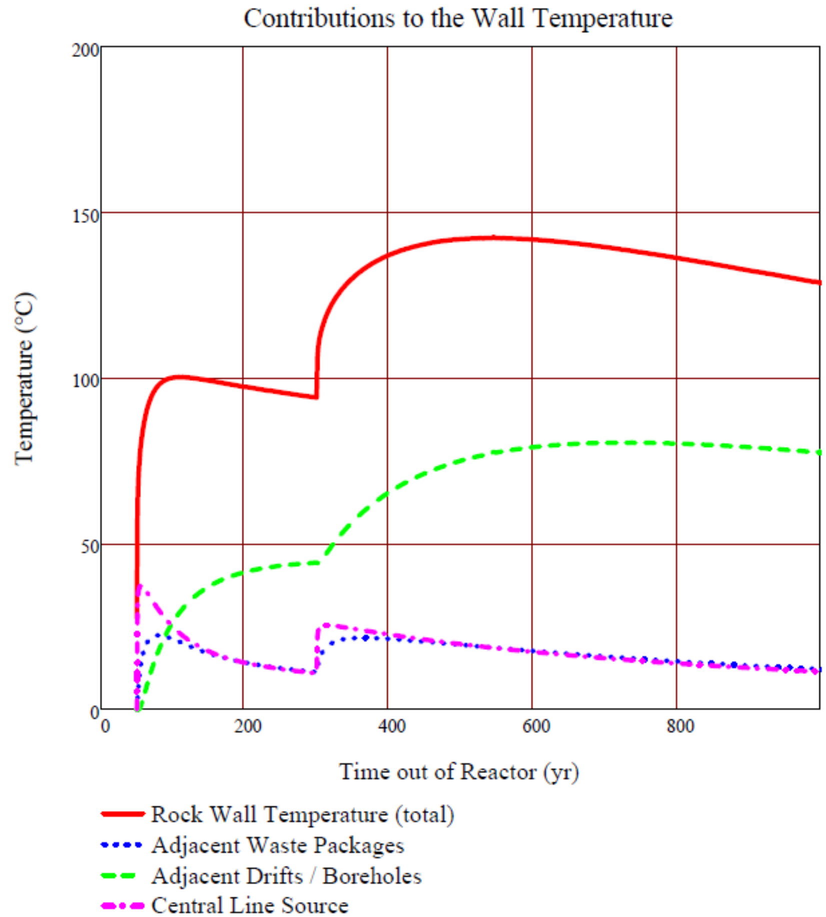


Figure B.3-2 Case 21b – 60% Ventilation efficiency

See Base Case 21, Figure B.3-4, for case parameters

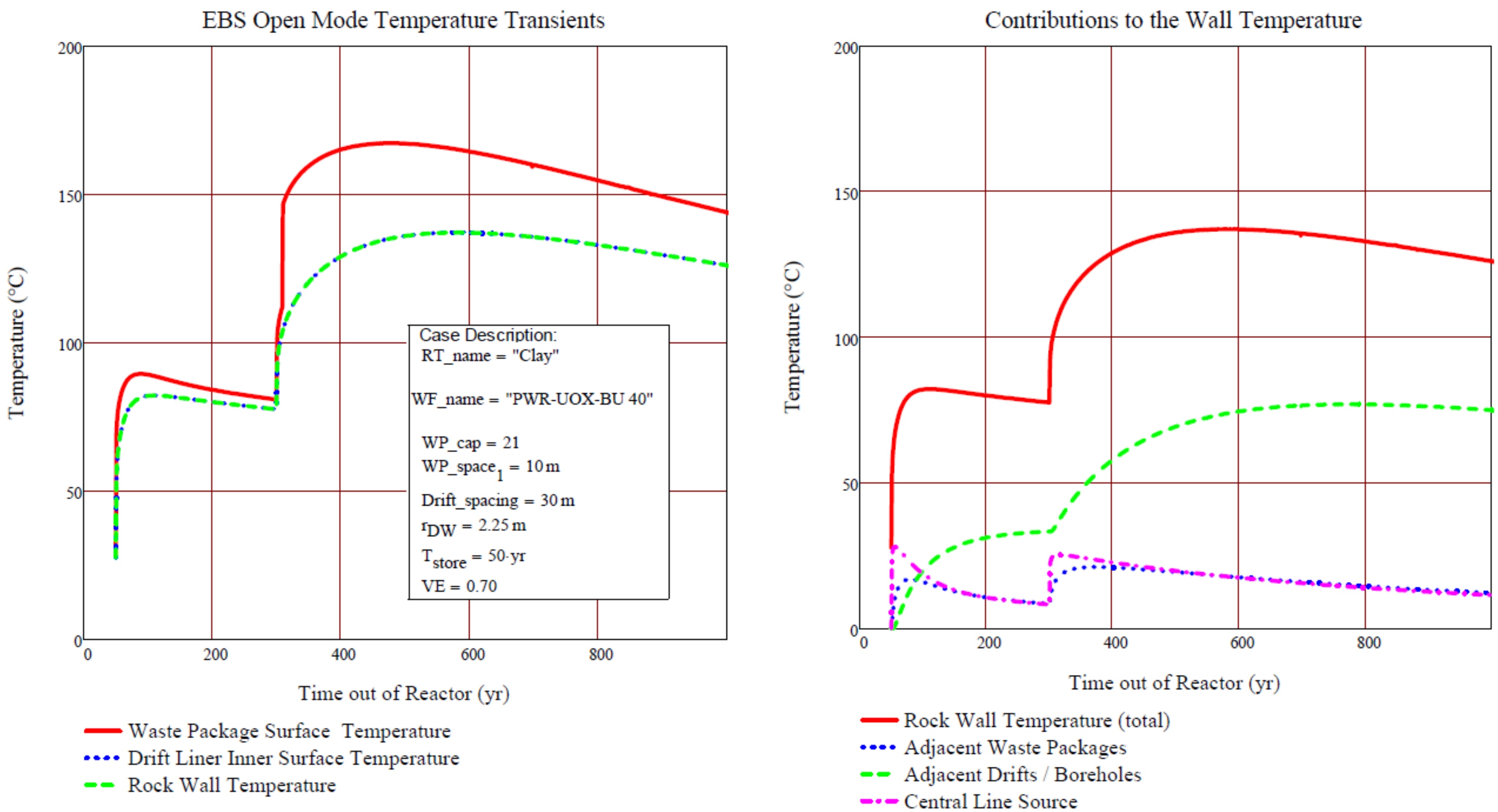


Figure B.3-3 Case 21c – 70% Ventilation efficiency

See Base Case 21, Figure B.3-4, for case parameters.

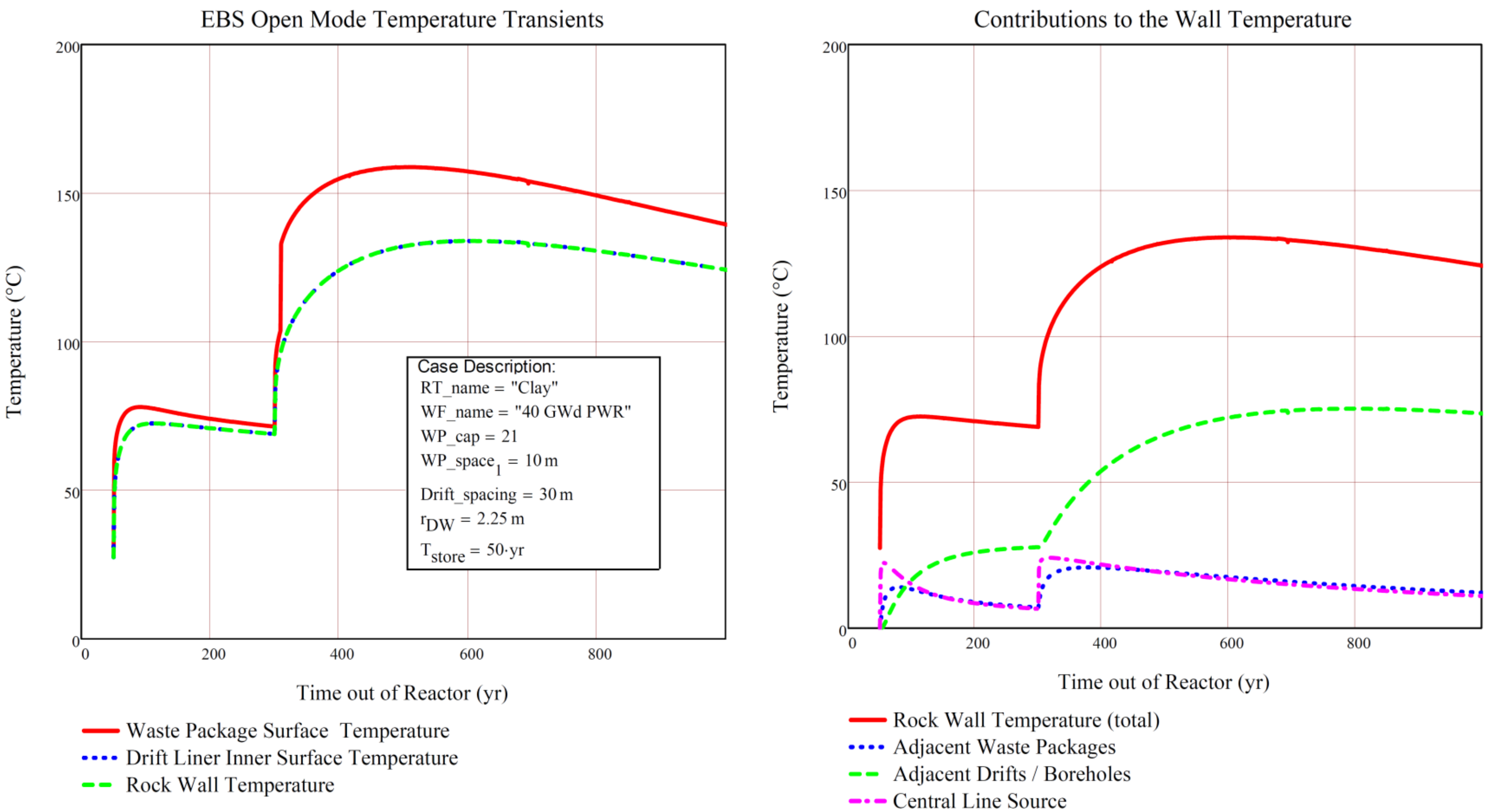


Figure B.3-4 Case 21 (base case for this sensitivity study) – 75% Ventilation efficiency

Clay medium, 21 PWR WPs with 40 GWd/MT burnup, and 250 yr ventilation after 50 yr storage.

This is a duplicate of Figure B.2-9

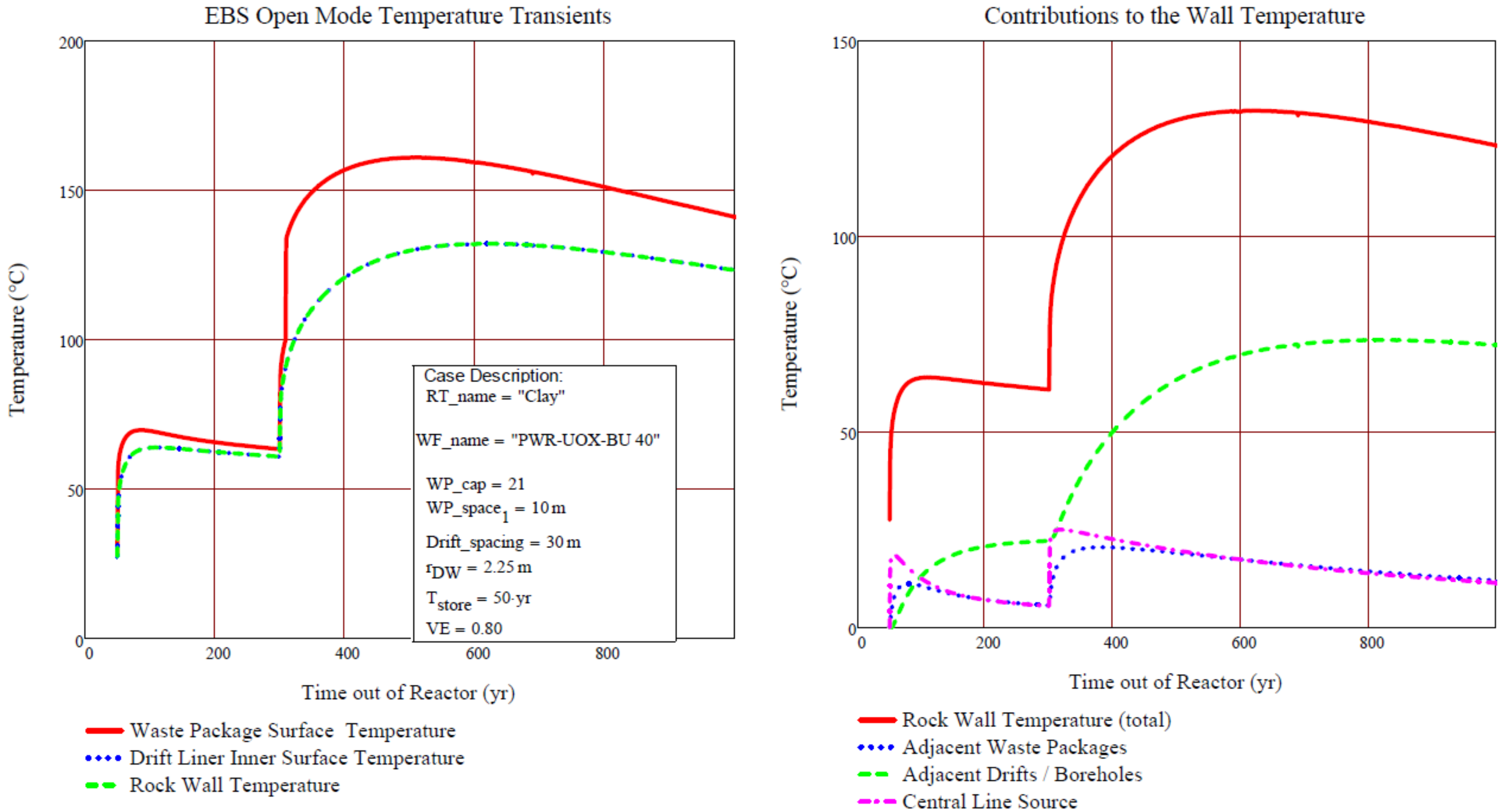


Figure B.3-5 Case 21d – 80% Ventilation efficiency

See Base Case 21, Figure B.3-4, for case parameters.

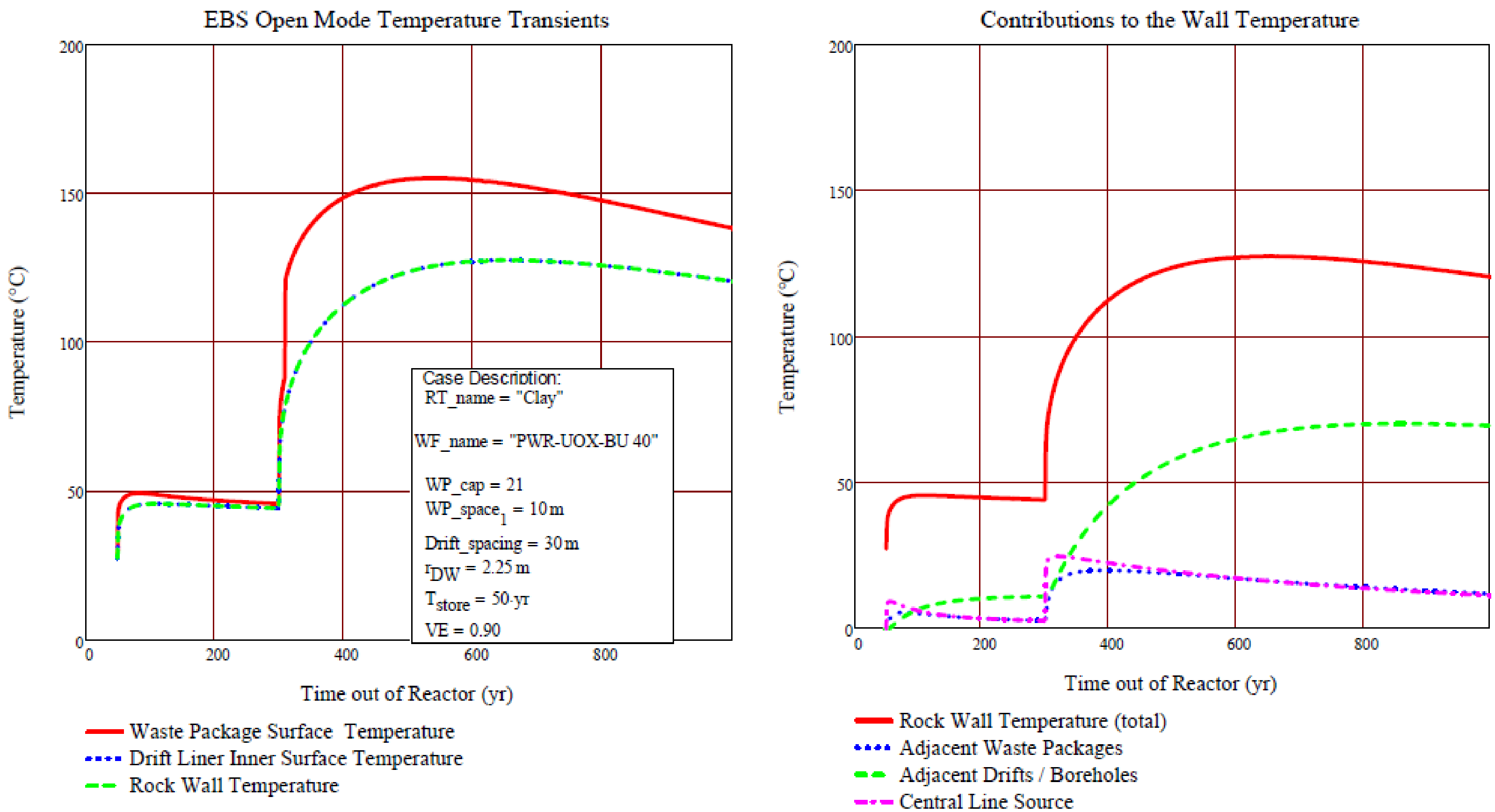


Figure B.3-6 Case 21e – 90% Ventilation efficiency

See Base Case 21, Figure B.3-4, for case parameters. This is the base case for the ventilation duration sensitivity study in Appendix B.3.2.

B.3.2 VENTILATION DURATION SENSITIVITY STUDY

Variation in ventilation duration of 50, 100, 150, and 200 years was investigated. These cases supplement the previously analyzed 250 years. All cases had 50 years of surface storage, 10 yr of backfill emplacement, 21-UOX WPs with 40 GWd/MT burnup, and are in a clay geologic medium. All are run with ventilation efficiency of 90%, at the upper end of the investigated range in Appendix B.3.1; thus, the base case for this sensitivity analysis is Case 21e from the ventilation efficiency sensitivity study rather than from the main array of open mode cases studied in Section B.2. For the 50 yr ventilation period, two additional sensitivity cases were investigated, with the nominal spacing of 30 m increased to 40 and then 50 m. Note that Case 21e is also used in Appendix B.3.1.

Table B.3-2 List of cases used in the ventilation duration sensitivity study for clay

This table assumes 50 yr of storage and 10 year of backfill emplacement. WPs are 21-UOX with 40 GWd/MT burnup. Ventilation efficiency is 90% (the base case is 21e, from Appendix B.3.1). Axial spacing is 10 m, and lateral (drift/borehole) spacing is 30 m, except for the last two cases. The last three cases explore how higher temperatures due to shorter ventilation can be compensated for by wider drift or borehole spacing.

Figure Number	Case Number	Ventilation Period, yr	Drift Spacing, m		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-7	**21e**	250	30		127.6	659		155.2	539
B.3-8	21f	200	30		134.3	602		164.3	479
B.3-9	21g	150	30		142.0	518		175.3	417
B.3-10	21h	100	30		152.0	424		190.1	314
B.3-11	21i	50	30		167.4	322		221.4	139
B.3-12	21j	50	40		141.3	349		207.5	118
B.3-13	21k	50	50		124.2	322		203.3	111

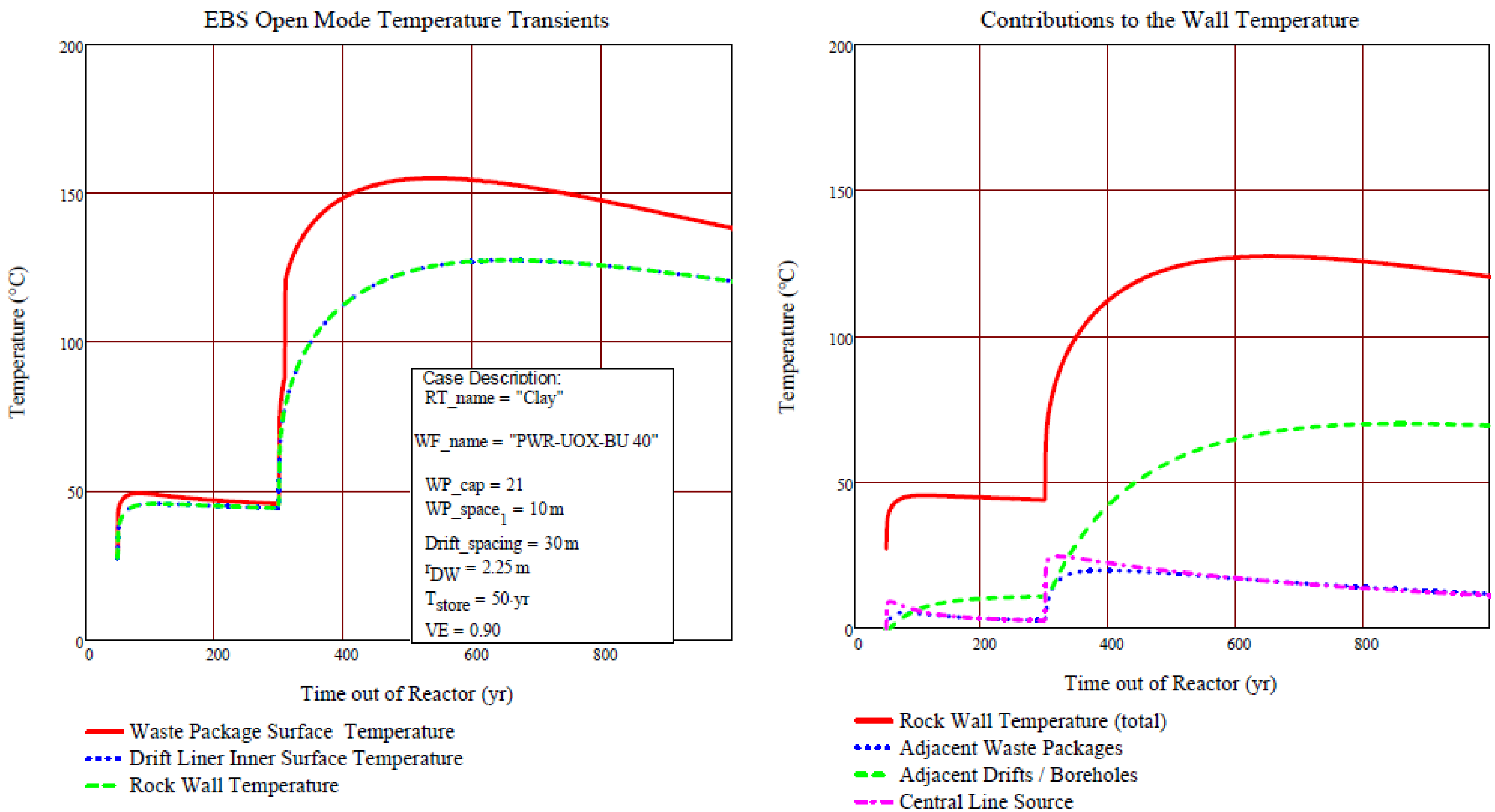
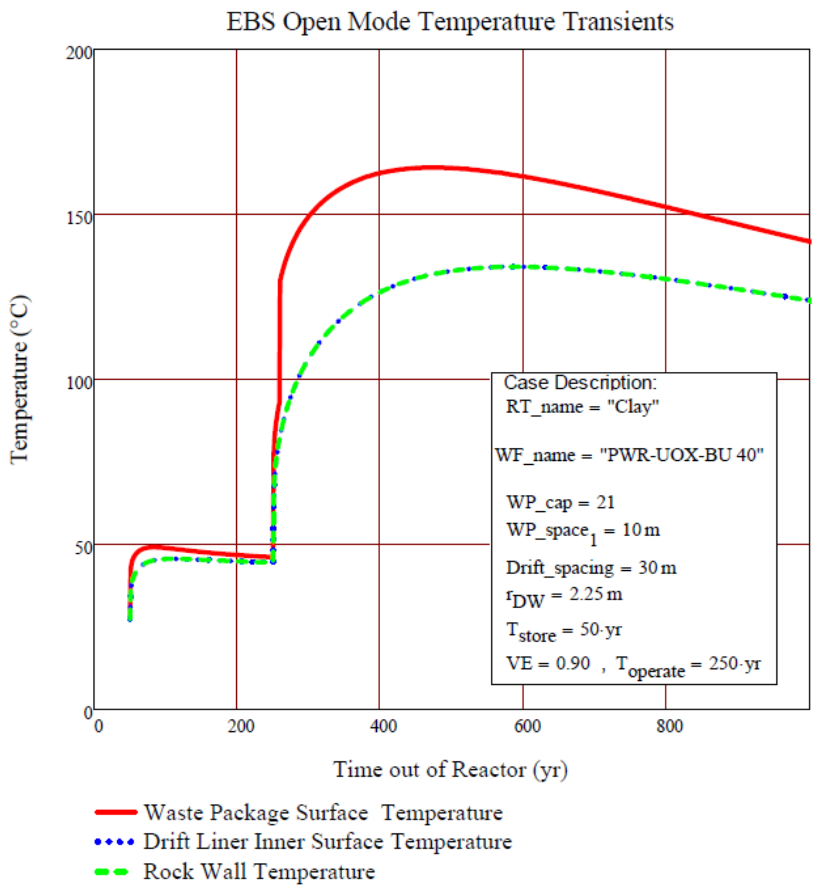


Figure B.3-7 Case 21e – 250 yr ventilation

This is the base case for the ventilation duration sensitivity study.



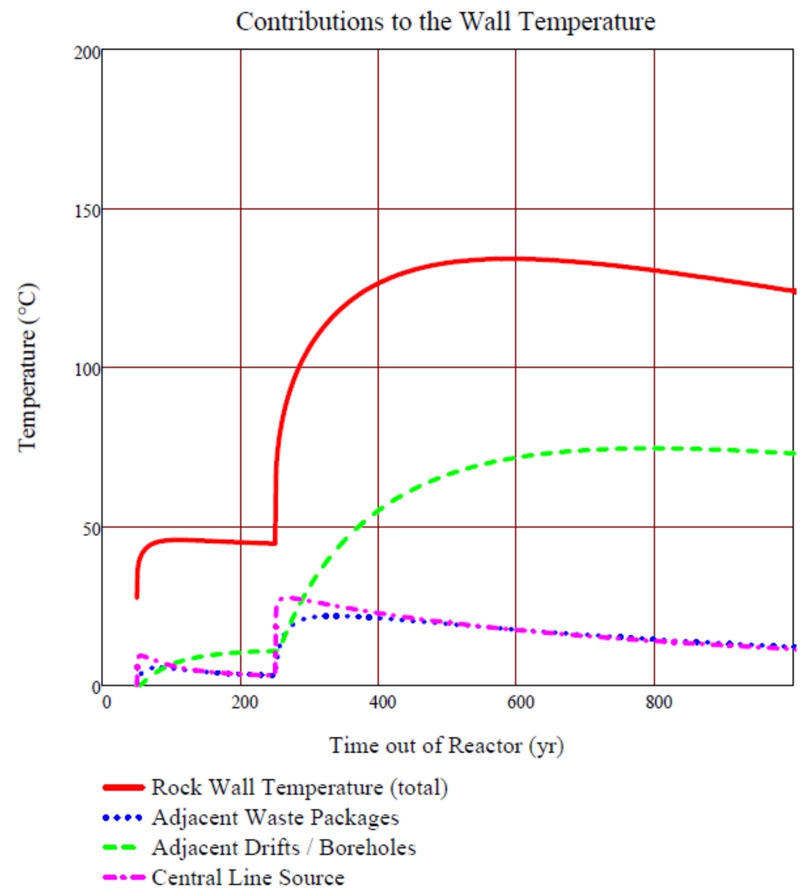


Figure B.3-8 Case 21f – 200 yr ventilation

See Base Case 21e, Figure B.3-7, for other parameters.

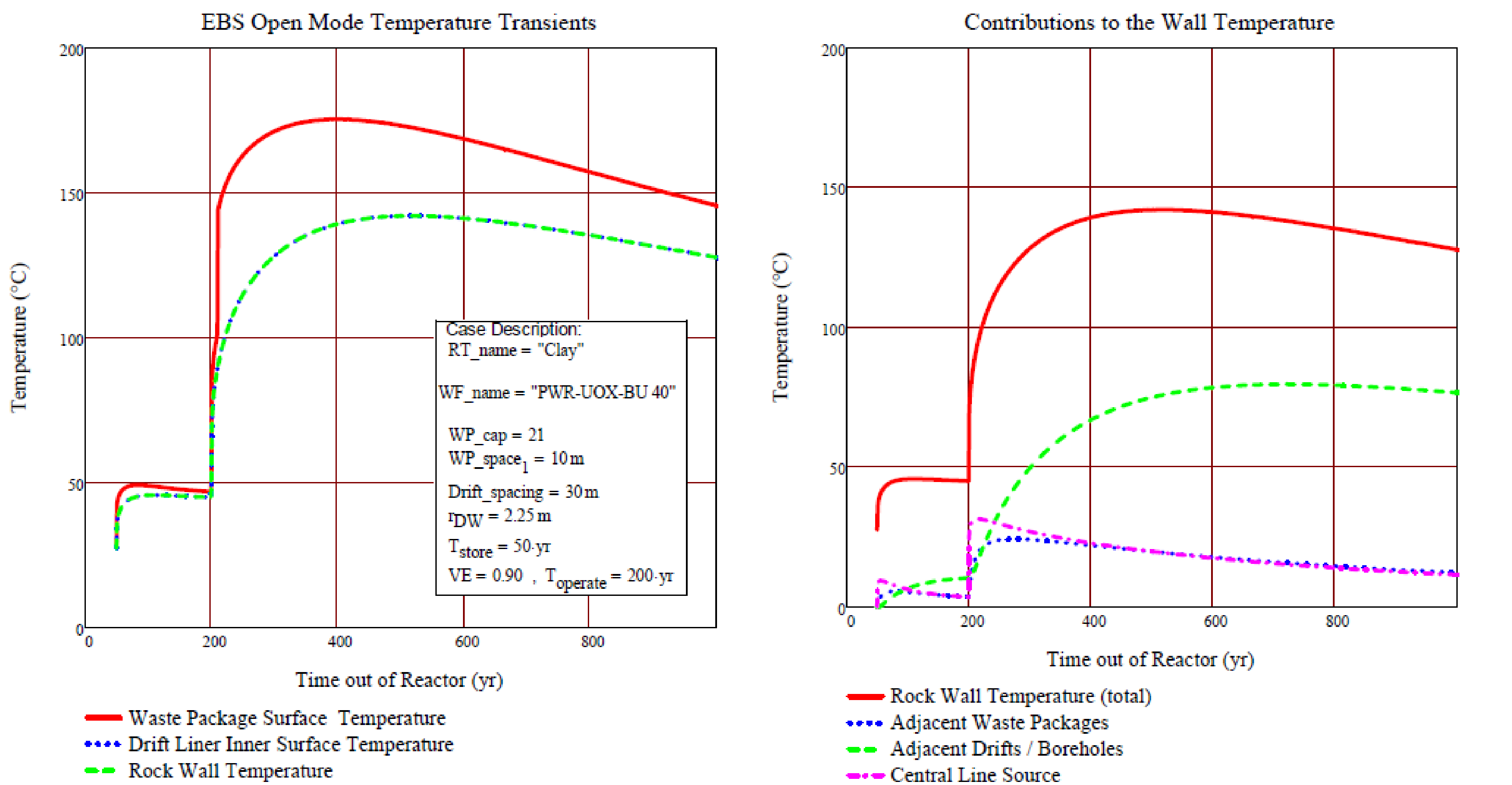
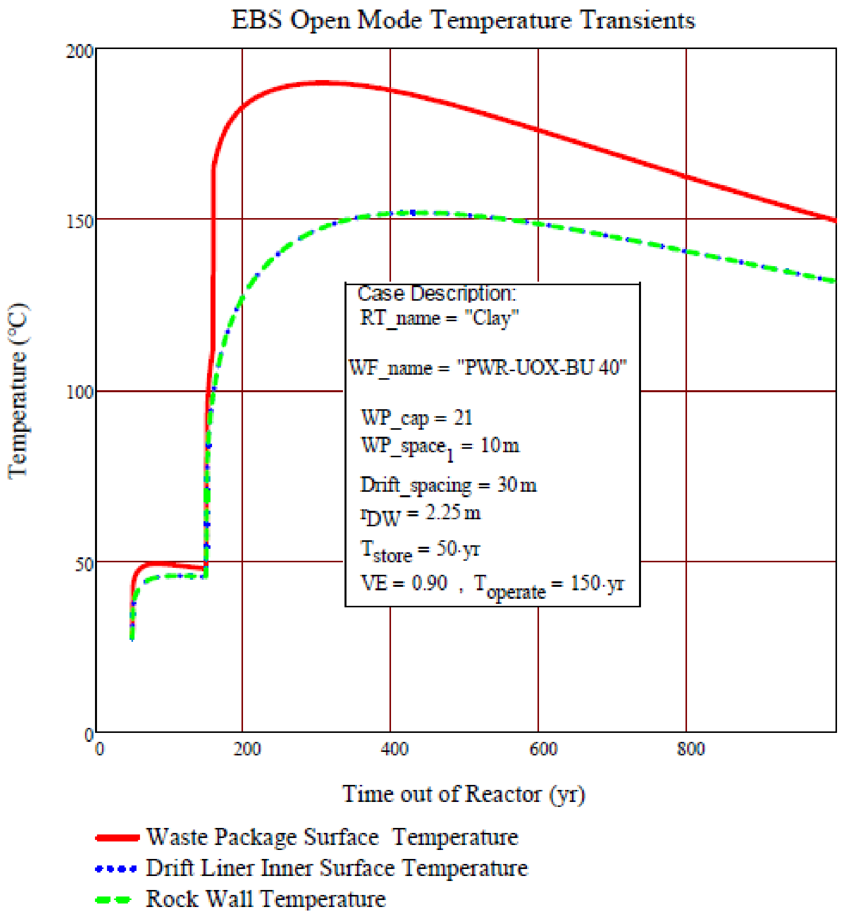


Figure B.3-9 Case 21g – 150 yr ventilation

See Base Case 21e, Figure B.3-7, for other parameters



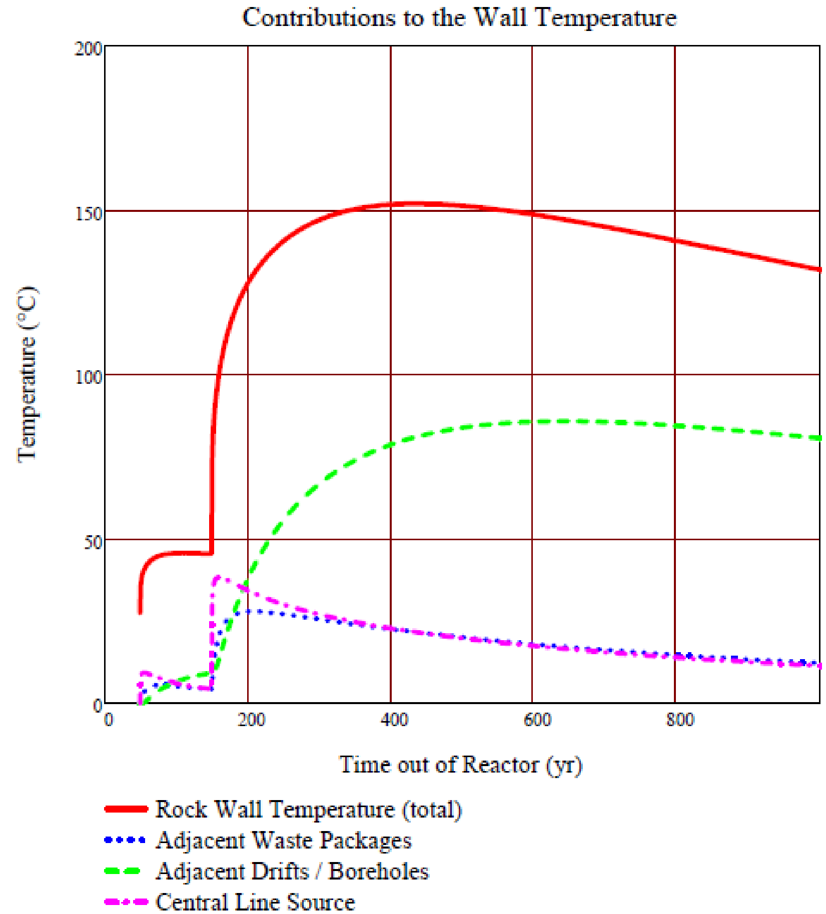


Figure B.3-10 Case 21h – 100 yr ventilation

See Base Case 21e, Figure B.3-7, for other parameters.

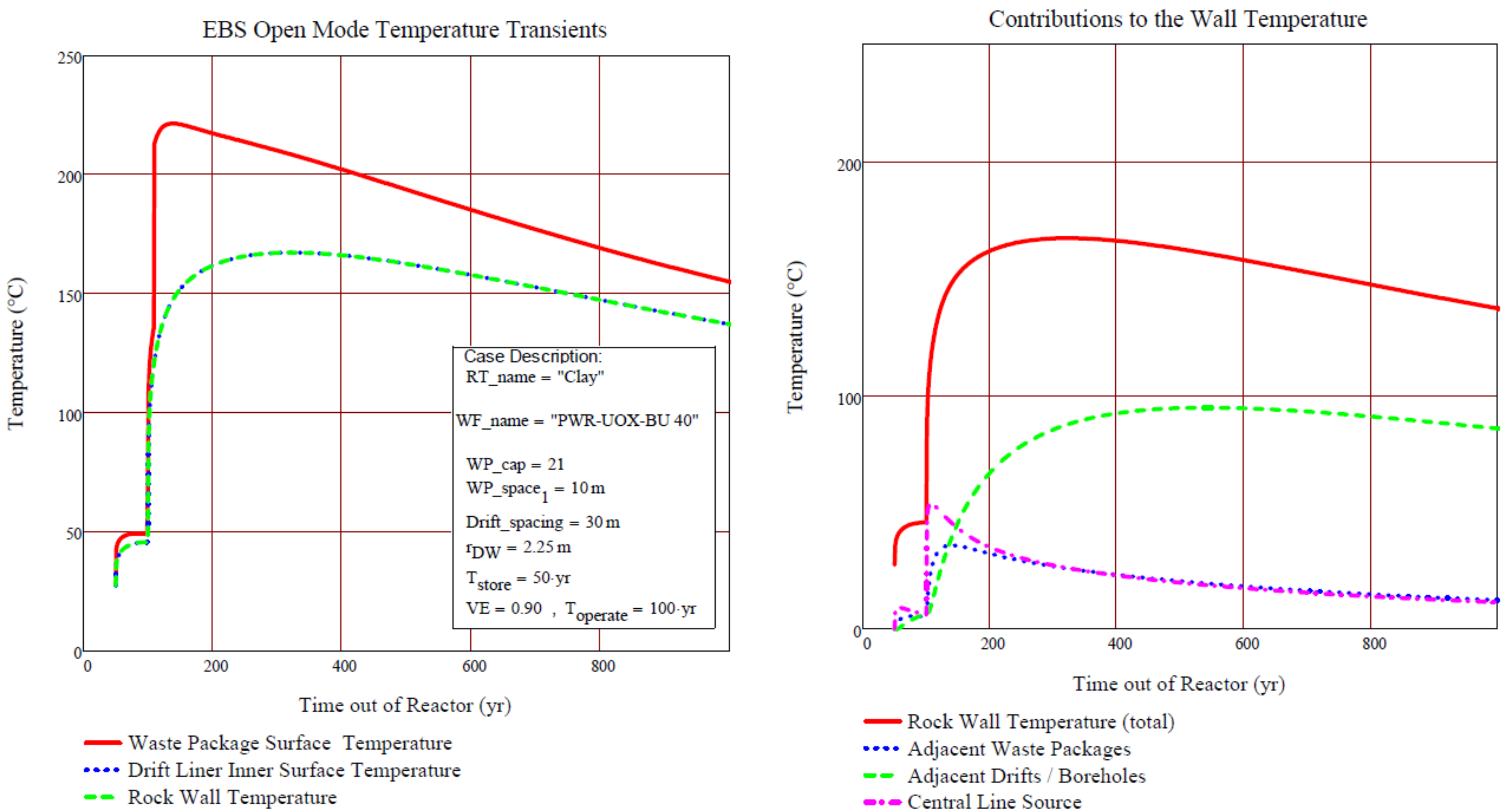


Figure B.3-11 Case 21i – 50 yr ventilation and 30 m lateral (drift/borehole) spacing

See Base Case 21e, Figure B.3-7, for other parameters. This is also a base case for the next two figures.

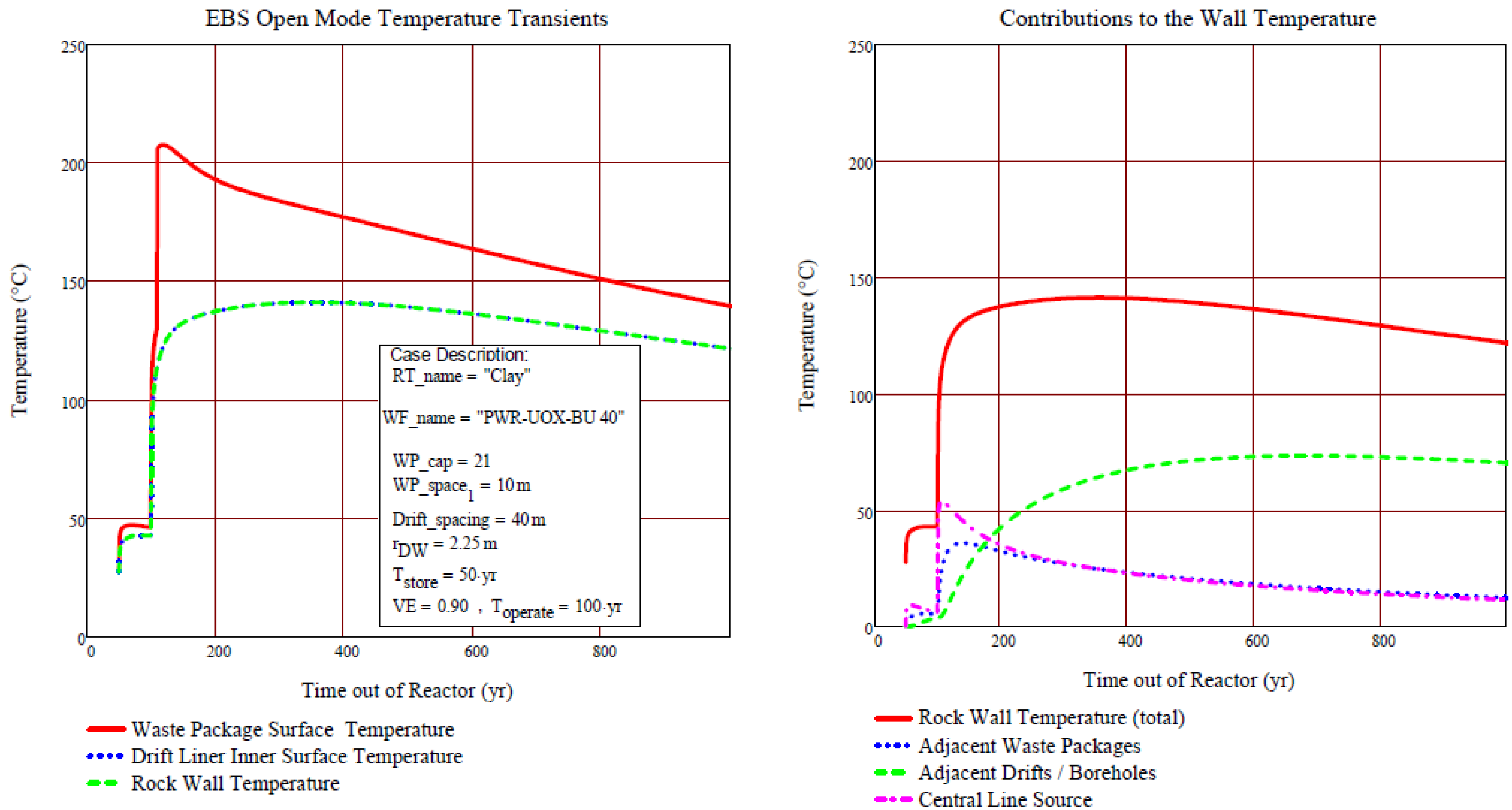


Figure B.3-12 Case 21j – 50 yr ventilation and 40 m lateral (drift/borehole) spacing.

See Base Cases 21e and 21i, Figures B.3-7 and B.3-11 for other parameters.

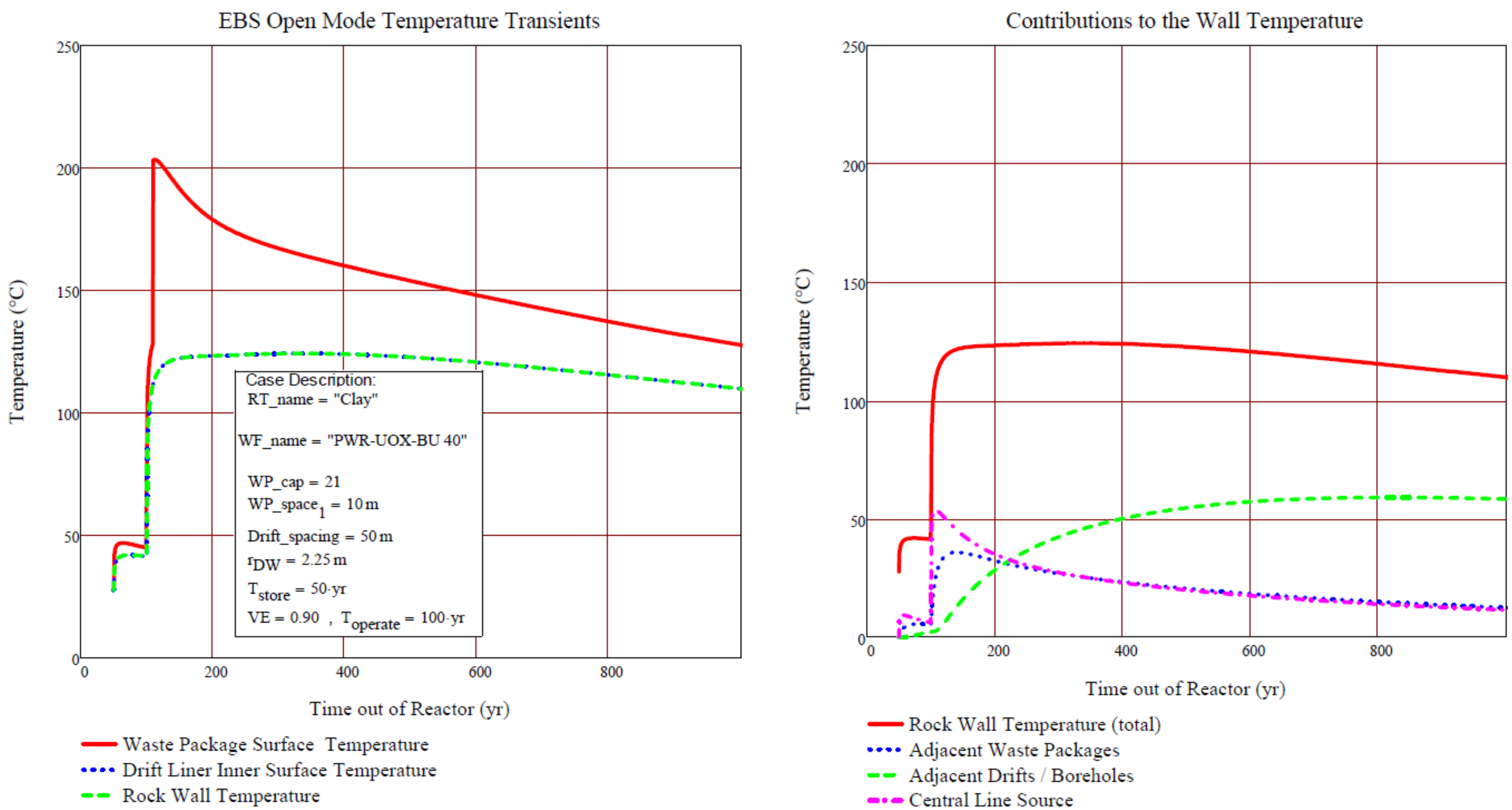


Figure B.3-13 Case 21k – 50 yr ventilation and 50 m lateral (drift/borehole) spacing

See Base Cases 21e and 21i, Figures B.3-7 and B.3-11 for other parameters.

B.3.3 Sensitivity to Drift/Borehole Spacing

Variation in lateral (drift/borehole) spacing is investigated. In addition to the base case spacing of 30 m, spacings of 40, 50, 60, and 70 m are shown. The base case for this study is Case 25, which has 32 PWR WPs with 40 GWd/MT burnup, in a clay medium. Axial spacing is 10 m; ventilation efficiency is 75%; and storage, ventilation and backfill installation times are 50, 250, and 10 yr, respectively.

Table B.3-3 List of cases used in the drift spacing sensitivity study for clay

21-UOX with 40 GWd/MT burnup in clay

Figure Number	Case Number	Drift Spacing, m		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-14	21	**30**		134.6	593		164.1	488
B.3-15	21w	40		116.1	641		145.3	470
B.3-16	21x	50		103.2	641		133.6	432
B.3-17	21y	60		94.0	641		126.6	378
B.3-18	21z	70		87.4	567		122.4	355

32-UOX with 40 GWd/MT burnup in clay

Figure Number	Case Number	Drift Spacing, m		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-19	**25**	**30**		190.7	593		225.2	516
B.3-20	25a	40		162.4	641		196.5	514
B.3-21	25b	50		142.9	641		178.0	468
B.3-22	25c	60		128.8	641		166.3	410
B.3-23	25d	70		118.7	567		159.3	374

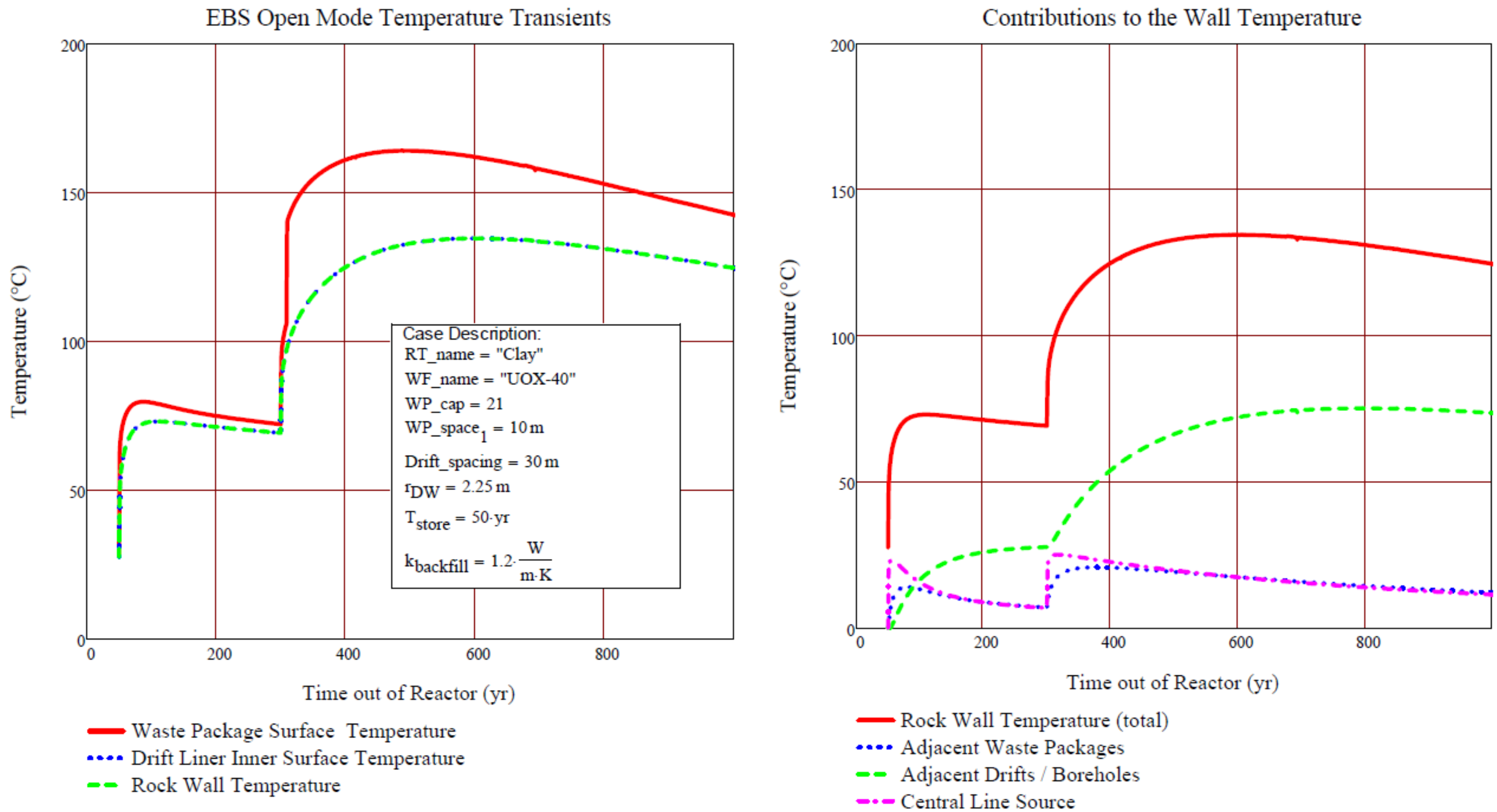


Figure B.3-14 Case 21 – 30 m lateral (drift/borehole) spacing. Clay medium, 21 UOX, 40 GWd/MT burnup

This is the base case for this sensitivity study which assumes 75% ventilation efficiency. This is a duplicate of Figure B.2-9

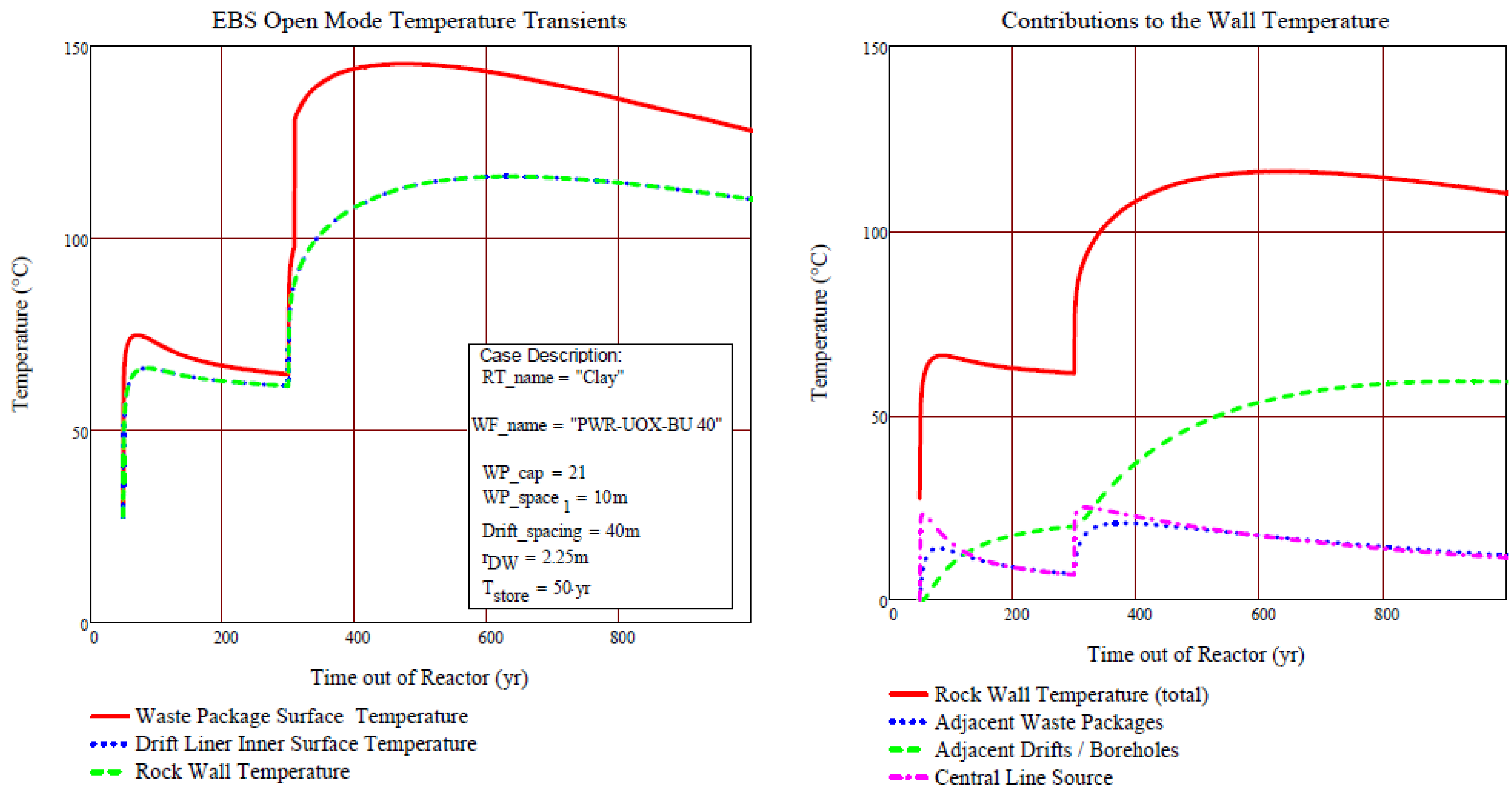


Figure B.3-15 Case 21w – 40 m lateral (drift/borehole) spacing – 21 UOX, 40 GWd/MT burnup

See Base Case 21, Figure B.3-9, for other parameters.

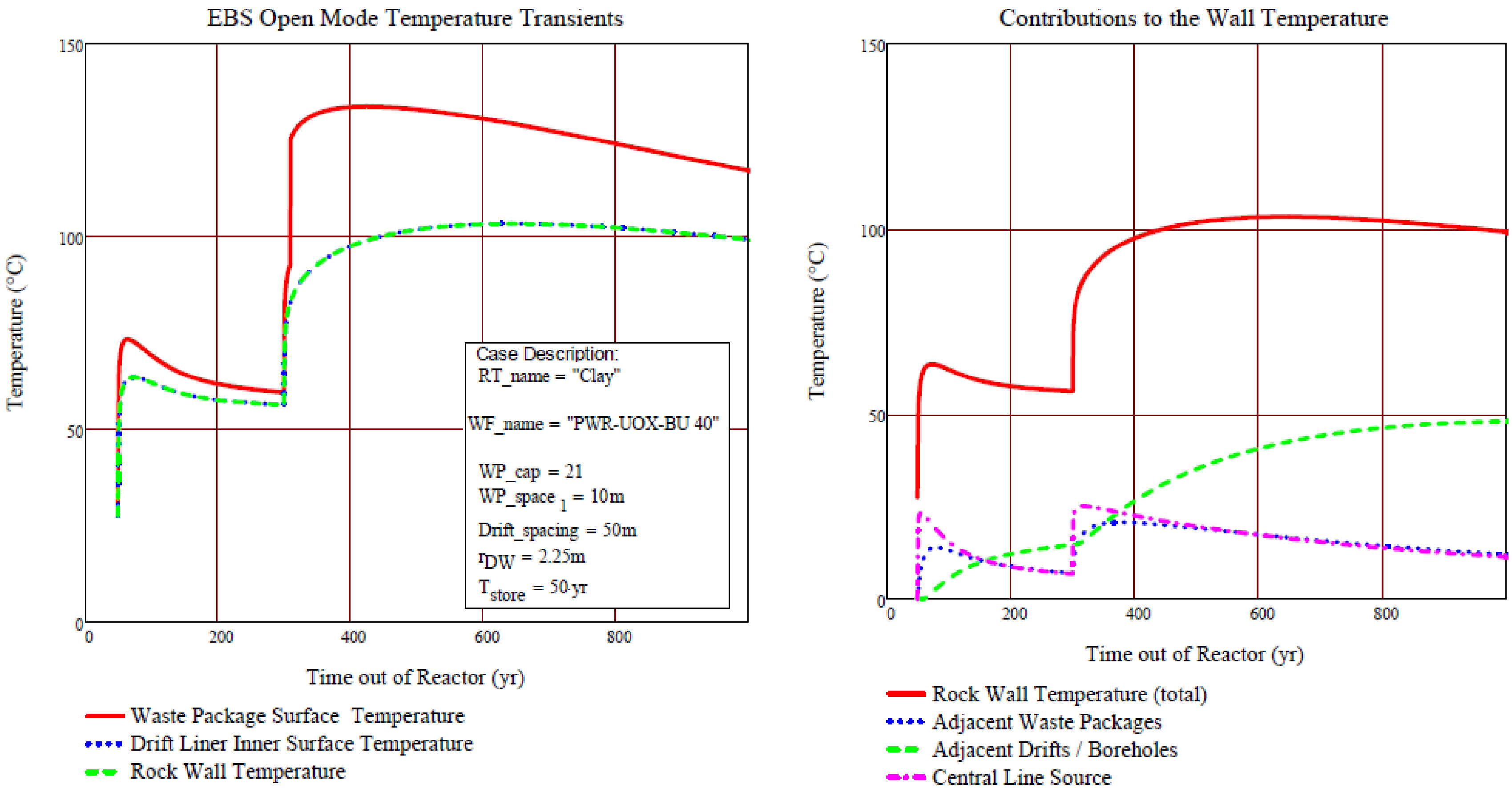


Figure B.3-16 Case 21x – 50 m lateral (drift/borehole) spacing – 21 UOX, 40 GWd/MT burnup

See Base Case 21, Figure B.3-9, for other parameters

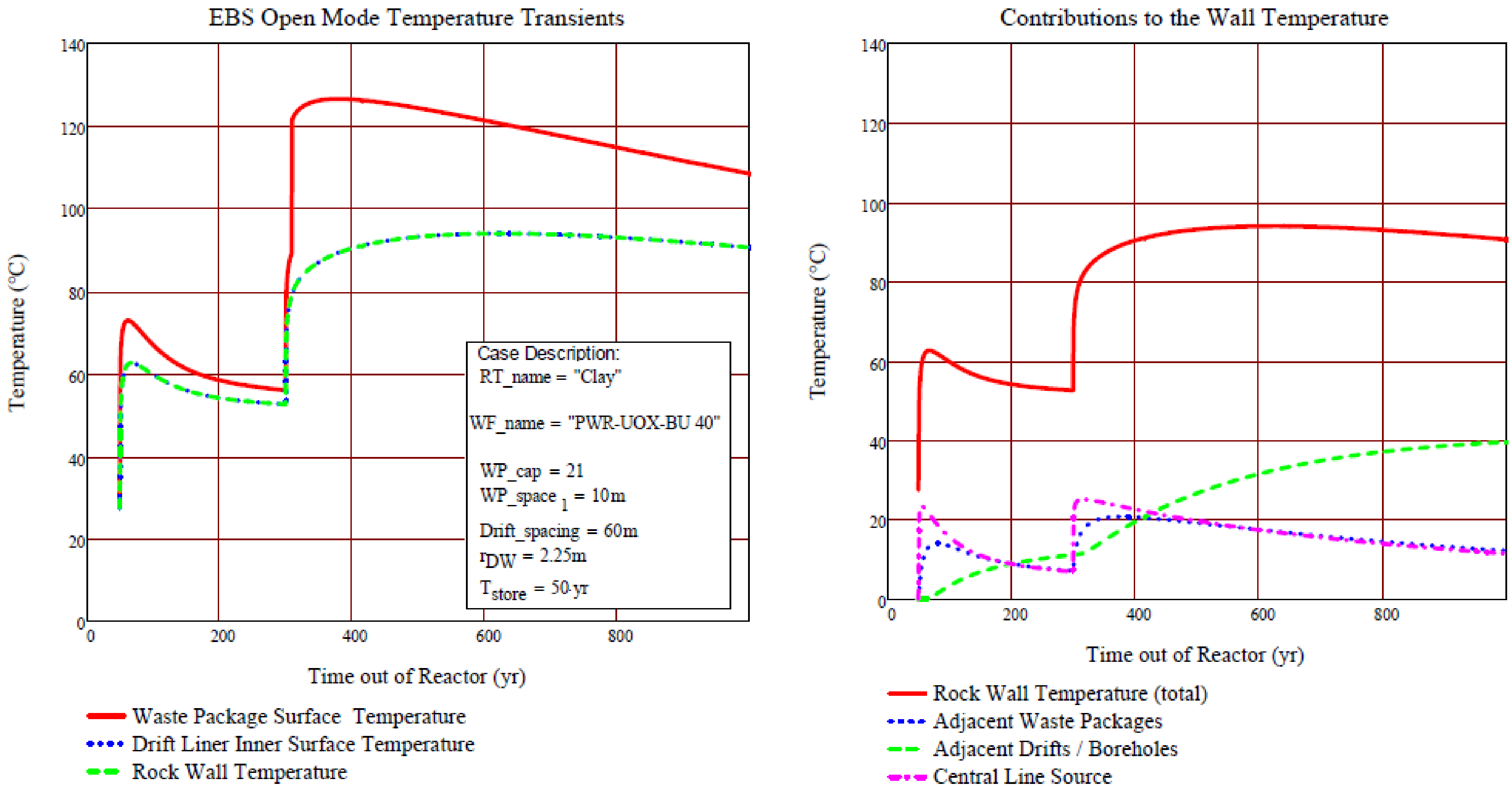


Figure B.3-17 Case 21y – 60 m lateral (drift/borehole) spacing – 21 UOX, 40 GWd/MT burnup

See Base Case 21, Figure B.3-9, for other parameters

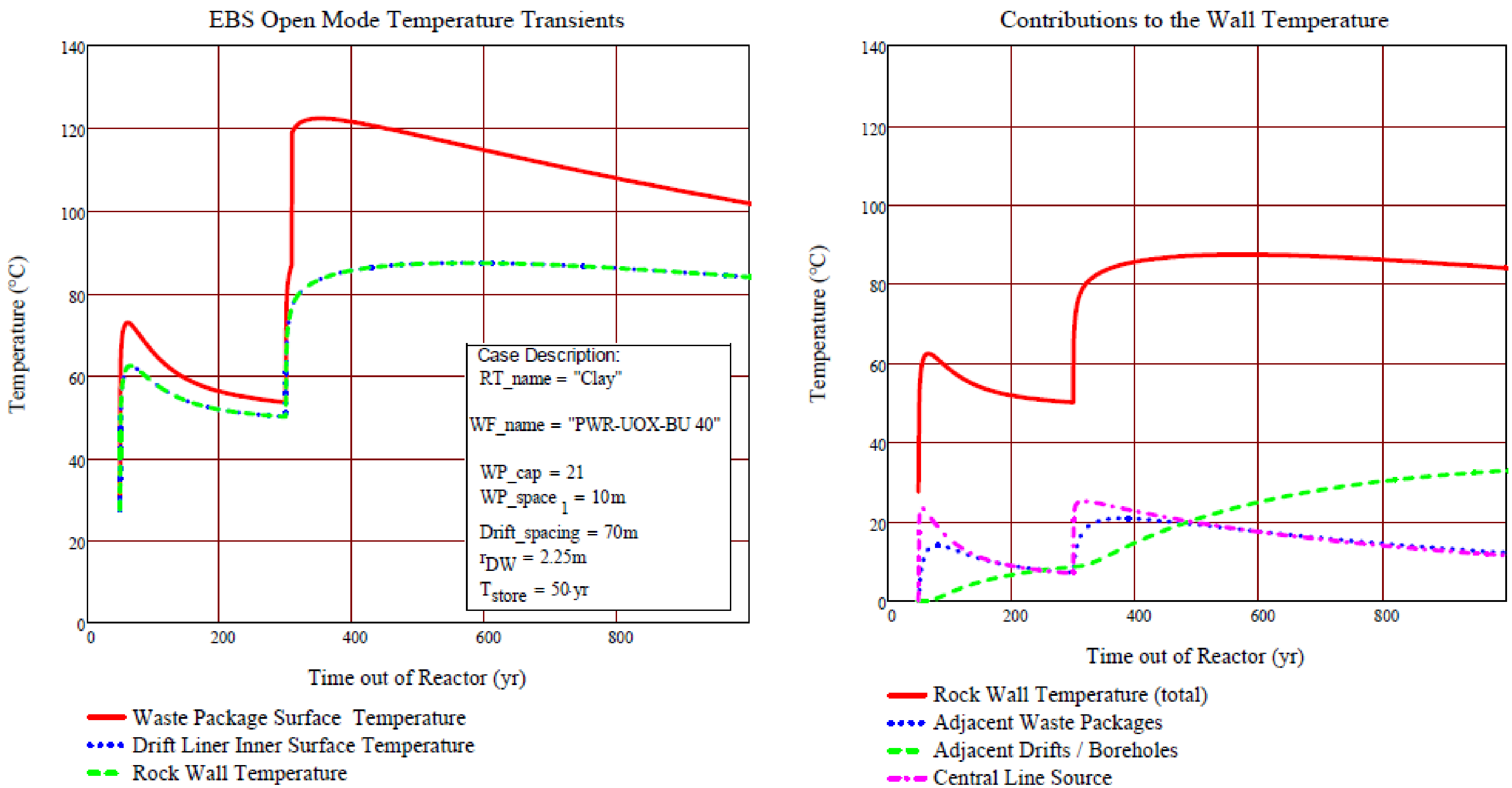


Figure B.3-18 Case 21z – 70 m lateral (drift/borehole) spacing – 21 UOX, 40 GWd/MT burnup

See Base Case 21, Figure B.3-9, for other parameters

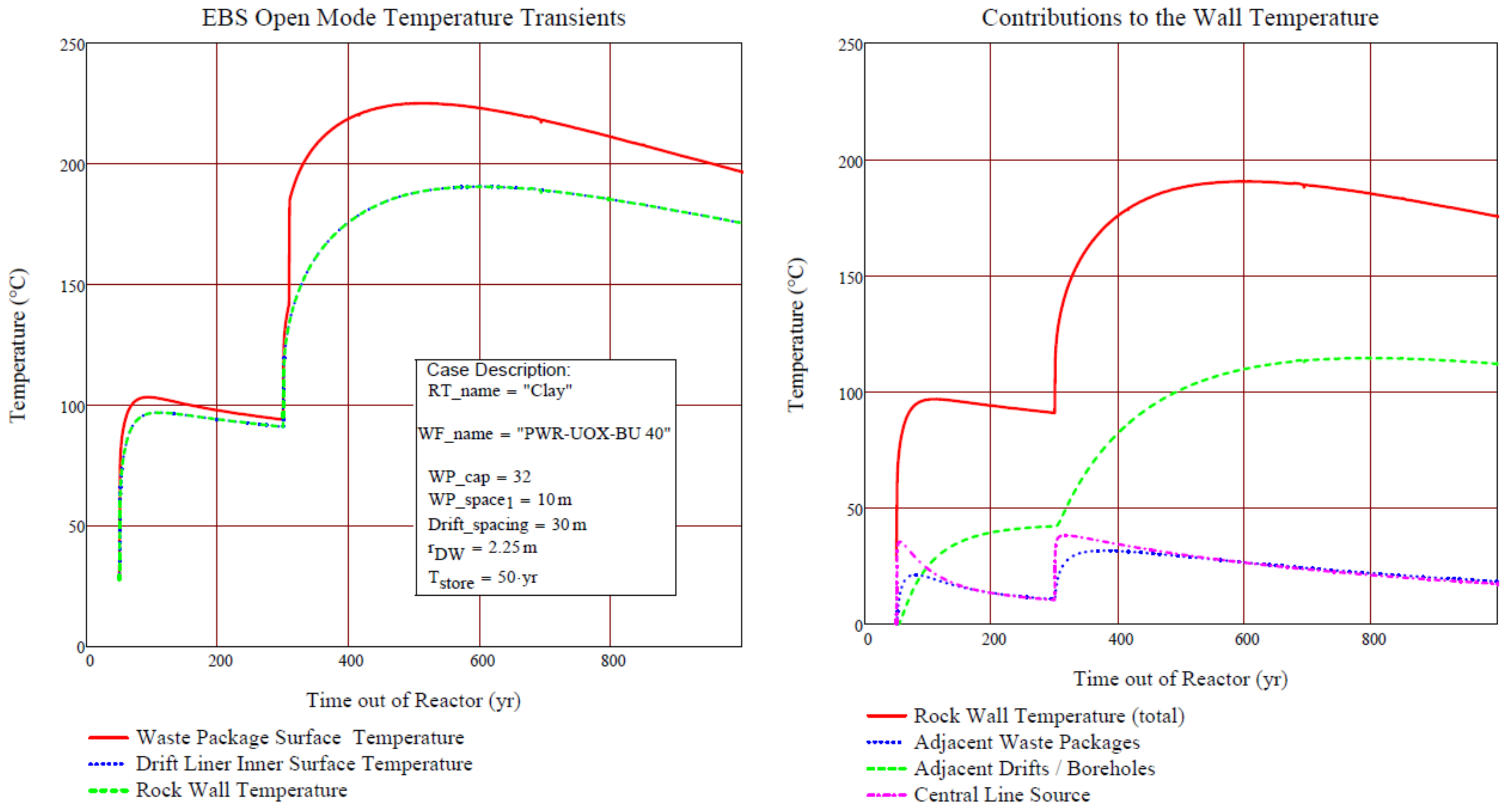


Figure B.3-19 Case 25 – 30 m lateral (drift/borehole) spacing. Clay medium, 32 PWR WPs

This case assumes 40 GWd/MT burnup, 50 yr storage before ventilation, 250 yr ventilation at 75% efficiency, and 10 yr of non-ventilated backfill installation before closure. This is the base case for this drift spacing sensitivity study. This is a duplicate of Figure B.2-13.

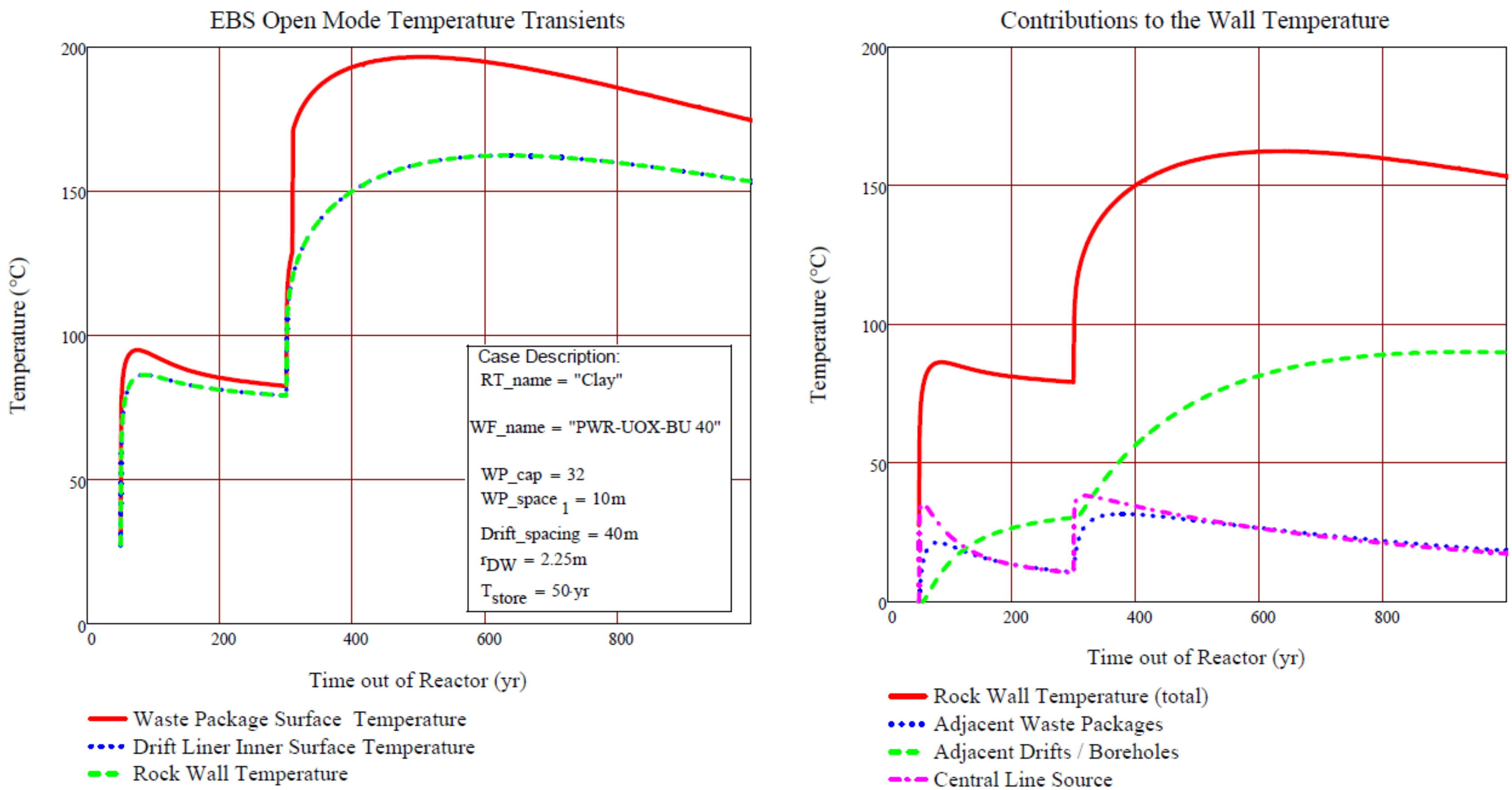


Figure B.3-20 Case 25a – 40 m lateral (drift/borehole) spacing – 32 UOX, 40 GWd/MT burnup

See Base Case 25, Figure B.3-14, for other parameters.

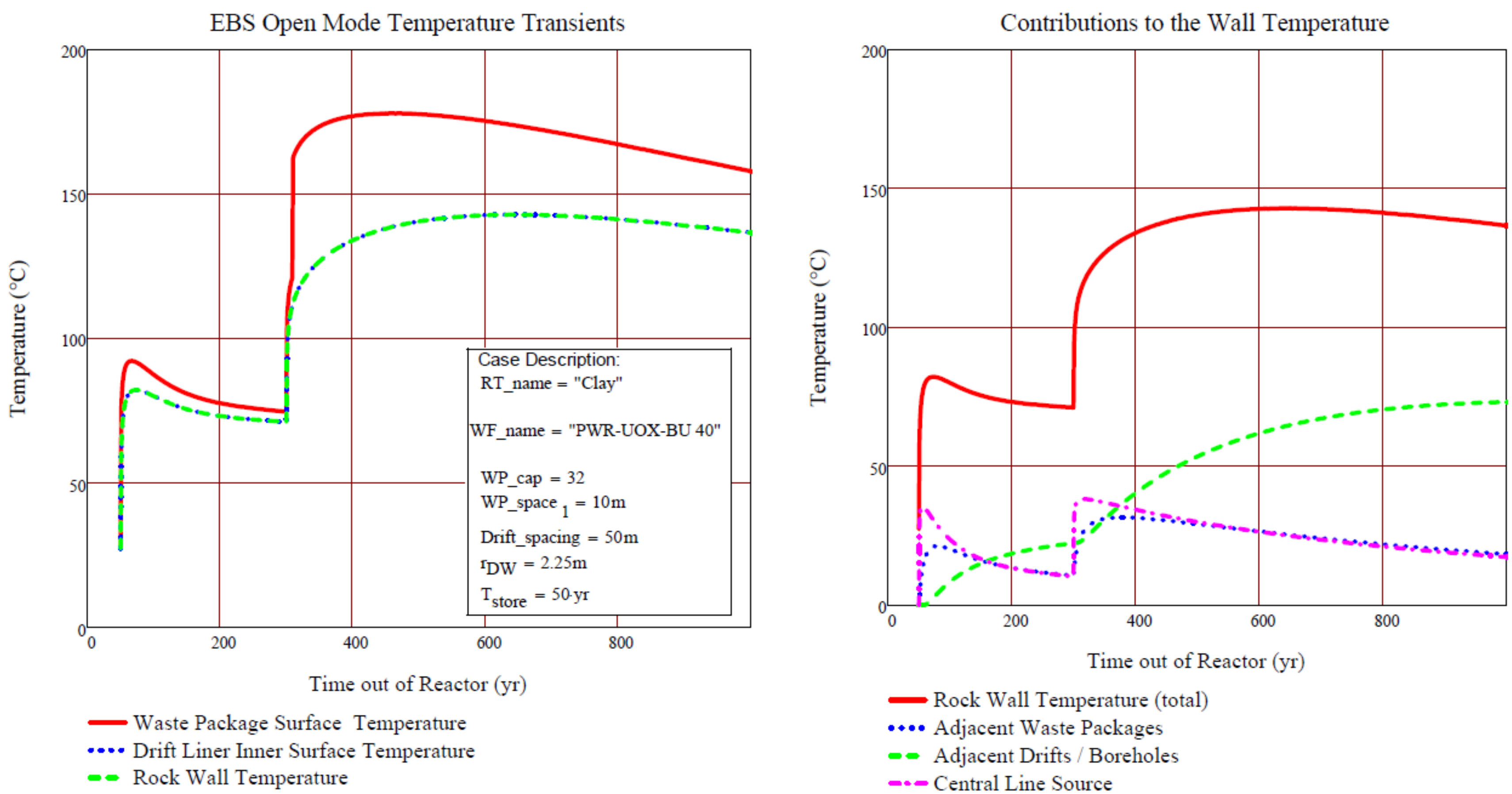


Figure B.3-21 Case 25b – 50 m lateral (drift/borehole) spacing – 32 UOX, 40 GWd/MT burnup

See Base Case 25, Figure B.3-14, for other parameters.

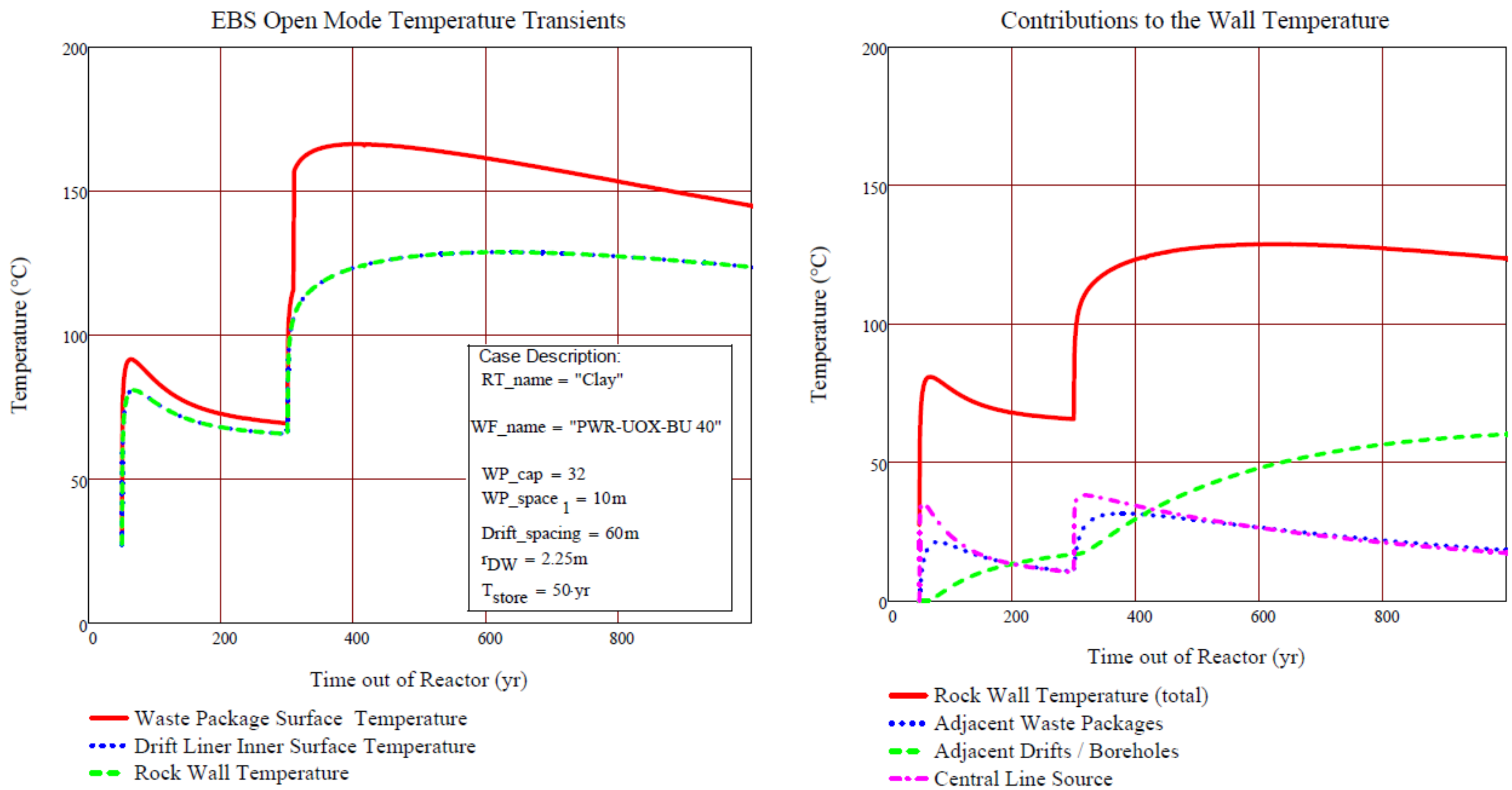


Figure B.3-22 Case 25c – 60 m lateral (drift/borehole) spacing – 32 UOX, 40 GWd/MT burnup

See Base Case 25, Figure B.3-14, for other parameters.

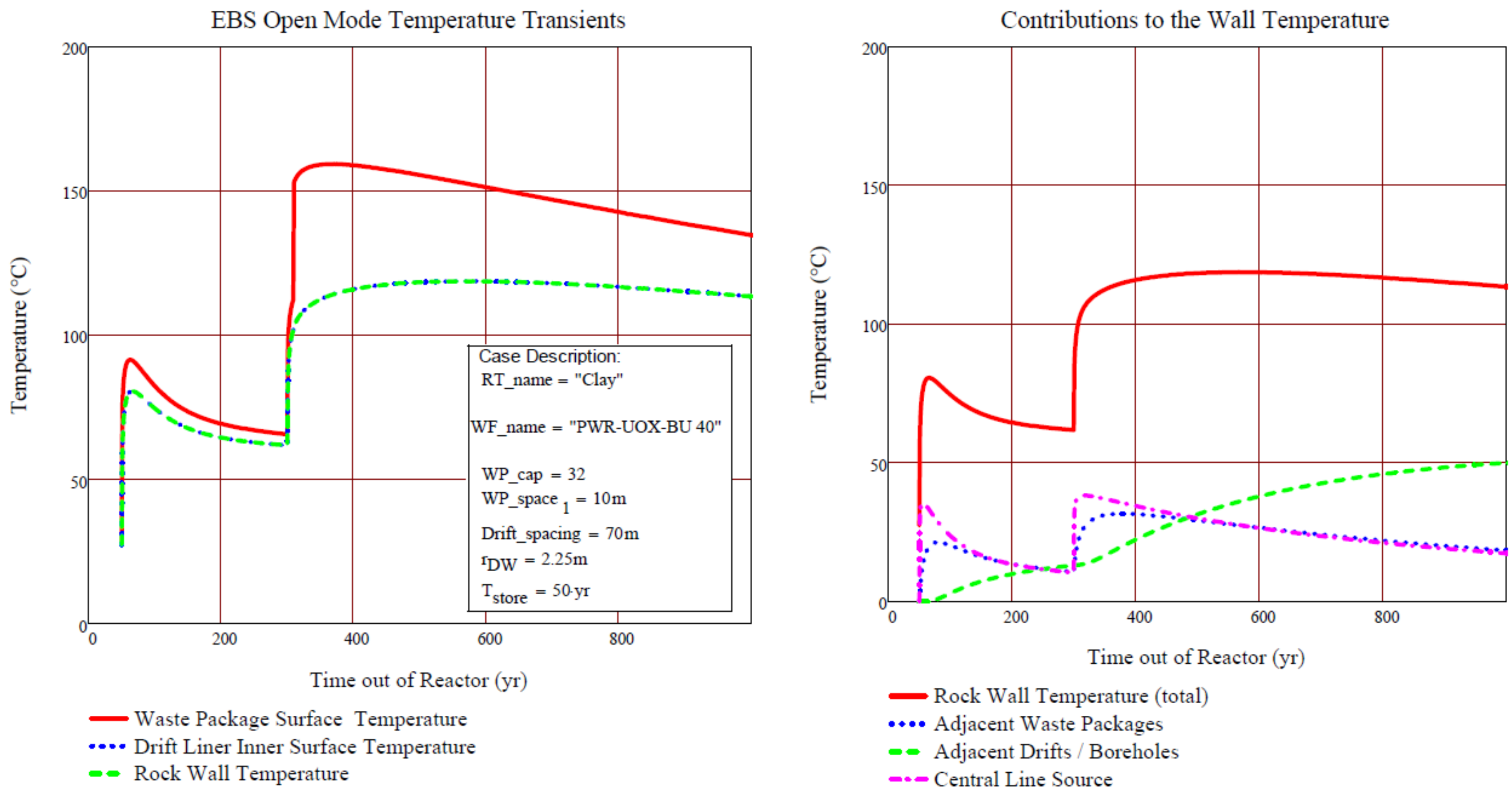


Figure B.3-23 Case 25d – 70 m lateral (drift/borehole) spacing – 32 UOX, 40 GWd/MT burnup

See Base Case 25, Figure B.3-14, for other parameters.

B.3.4 Sensitivity to Generic Host Rock Thermal Conductivity

A generic host rock with a range of thermal conductivity between 1 and 5 W/m-K is investigated. Thermal diffusivity is based on nominal volumetric heat capacity. The generic conductivities in the table envelope the base cases of 1.75 W/m-K for clay and 1.1 W/m-K for alluvium. These cases use 50 yr storage, 250 yr ventilation at 75% efficiency, 10 yr backfill emplacement, and 21-UOX WPs with 40 and 60 GWd/MT burnup.

Table B.3-4 Cases used in the generic host rock thermal conductivity sensitivity study

Figure Number	Case Number	Burnup, GWd/MT	Thermal Conductivity, W/m-K		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-24	57	40	1		182.4	641		209.9	547
B.3-25	58	40	2		125.8	604		155.3	488
B.3-26	59	40	3		101.4	567		132.8	442
B.3-27	60	40	4		87.8	526		120.3	417
B.3-28	61	40	5		78.9	526		112.2	405
B.3-29	62	60	1		217.7	624		252.0	515
B.3-30	63	60	2		147.7	567		185.1	439
B.3-31	64	60	3		118.4	518		157.8	410
B.3-32	65	60	4		101.8	495		142.5	393
B.3-33	66	60	5		90.6	491		132.6	370

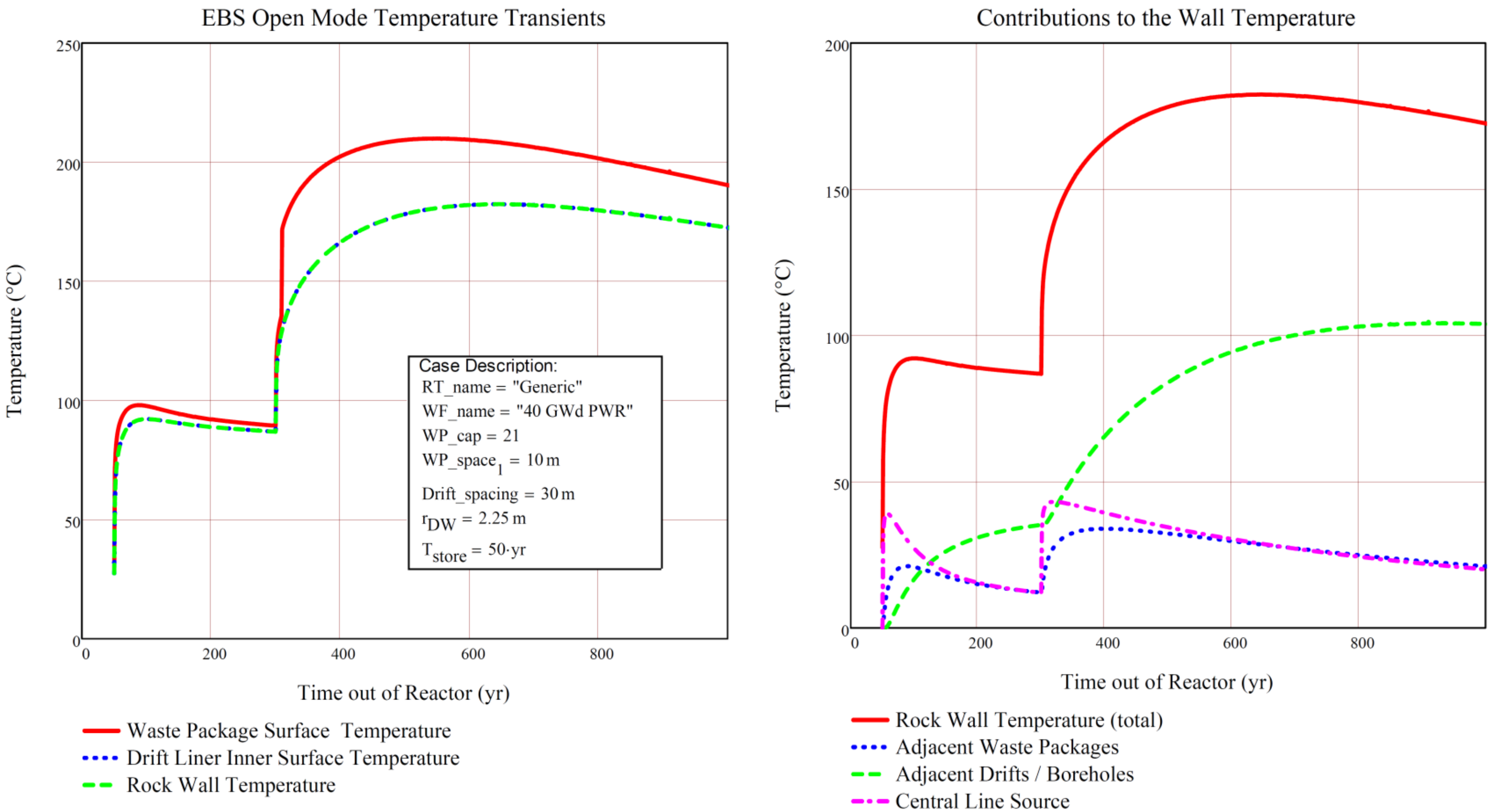


Figure B.3-24 Case 57 – Thermal conductivity of 1 W/m-K and burnup of 40 GWd/MT

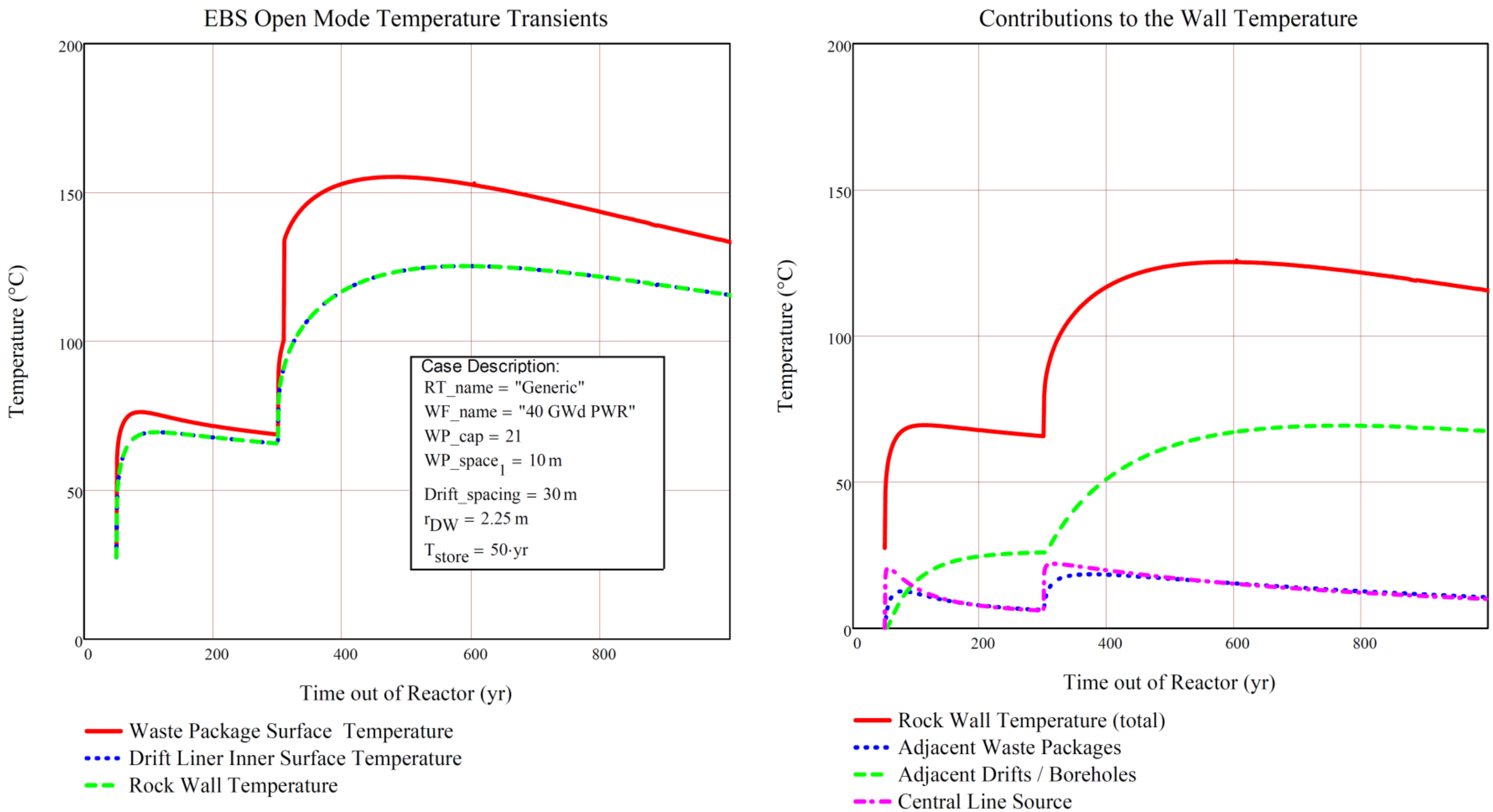


Figure B.3-25 Case 58 – Thermal conductivity of 2 W/m-K and burnup of 40 GWd/MT

See Case 57, Figure B.3-19, for other parameters.

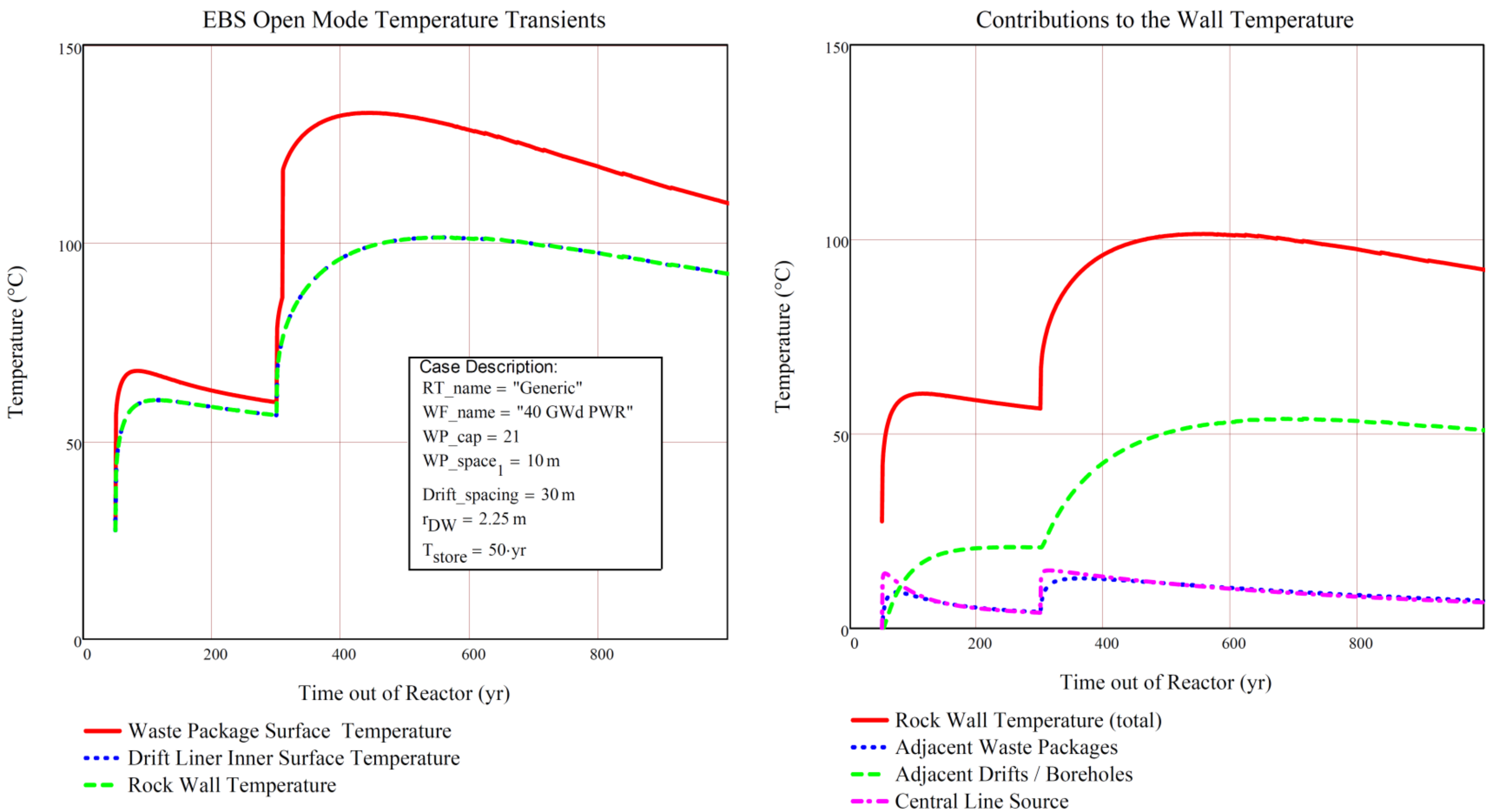


Figure B.3-26 Case 59 – Thermal conductivity of 3 W/m-K and burnup of 40 GWd/MT

See Case 57, Figure B.3-19, for other parameters.

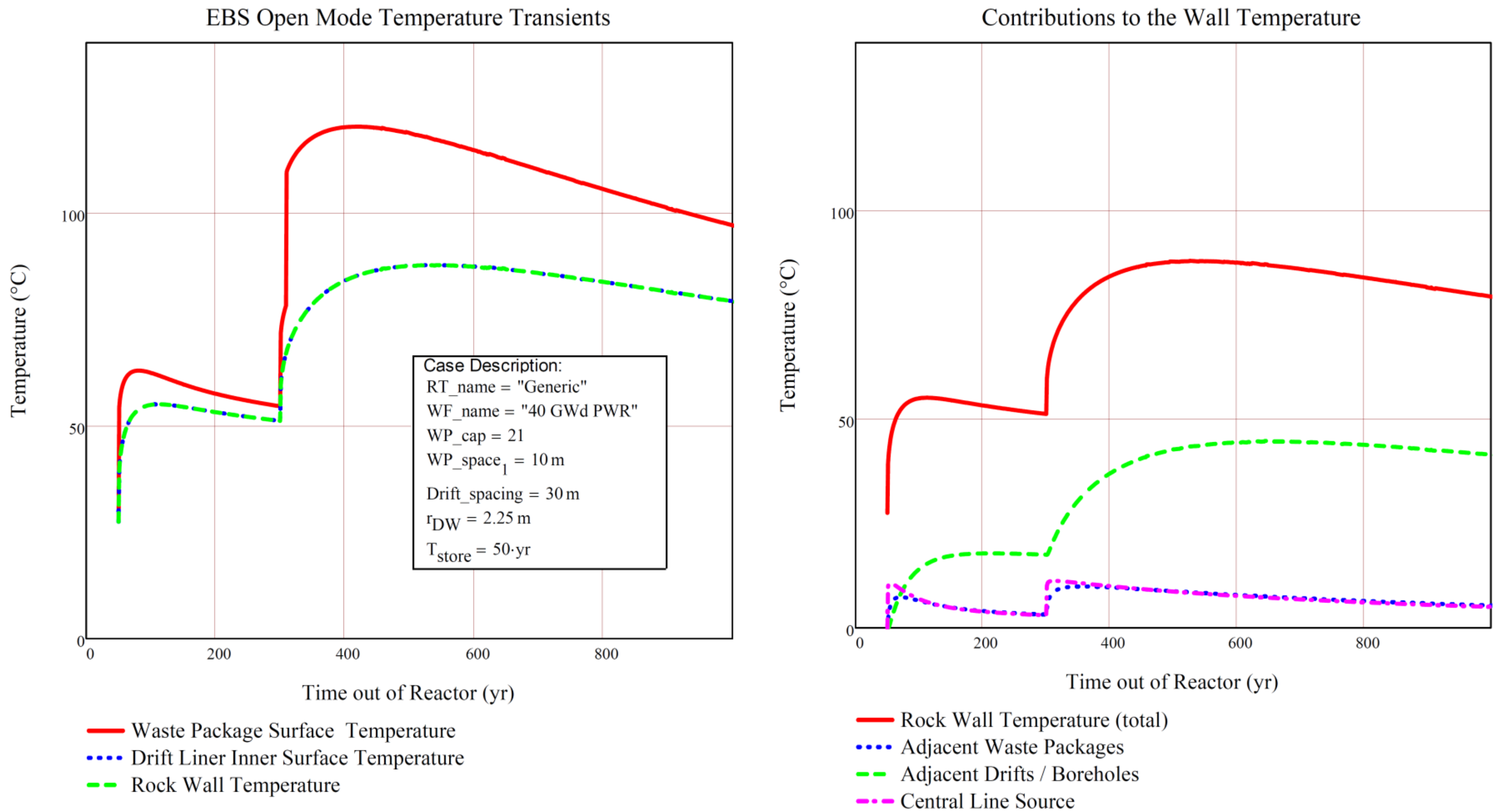
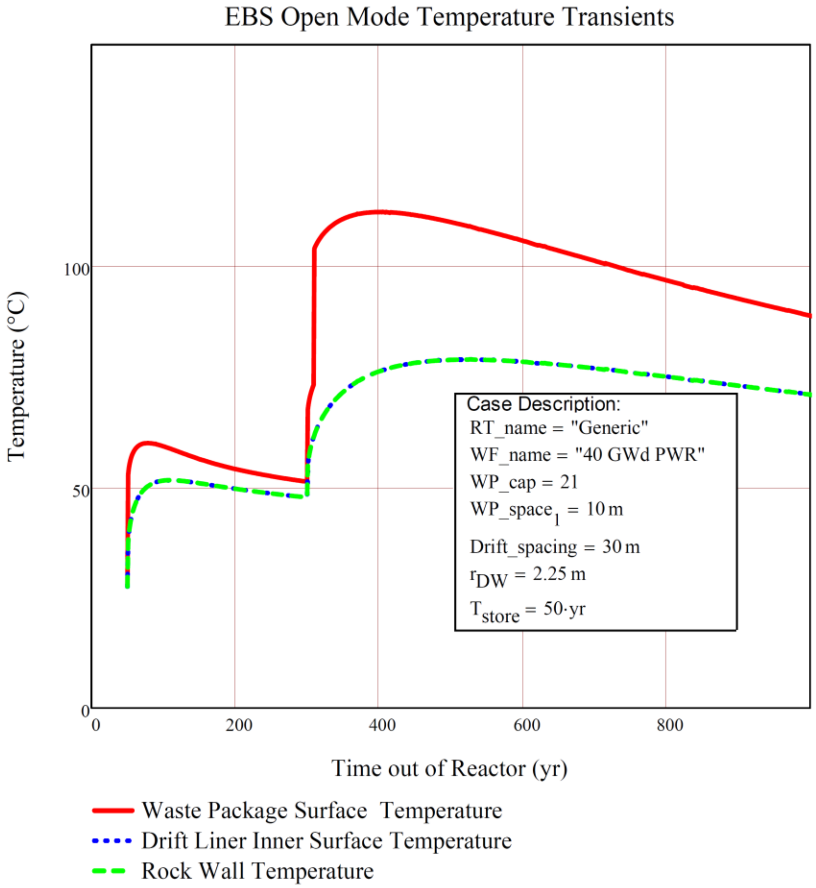


Figure B.3-27 Case 60 – Thermal conductivity of 4 W/m-K and burnup of 40 GWd/MT

See Case 57, Figure B.3-19, for other parameters.



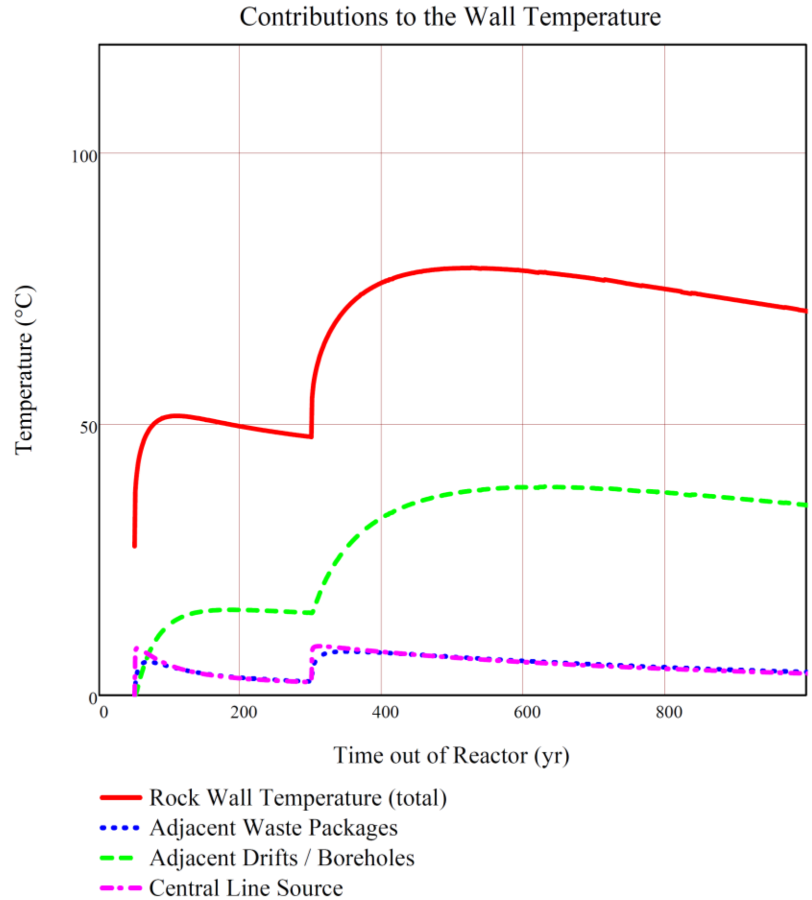


Figure B.3-28 Case 61 – Thermal conductivity of 5 W/m-K and burnup of 40 GWd/MT

See Case 57, Figure B.3-19, for other parameters.

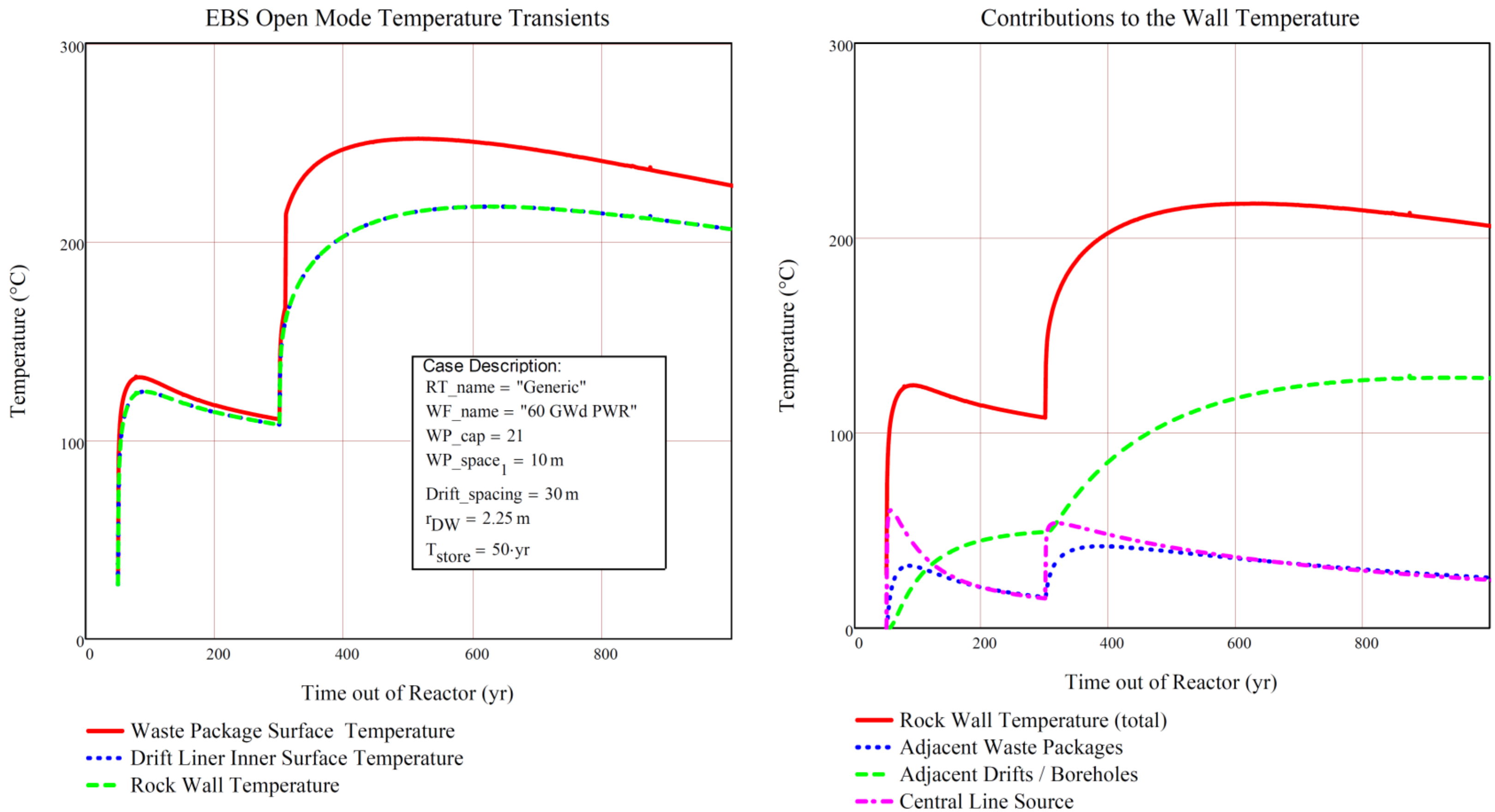
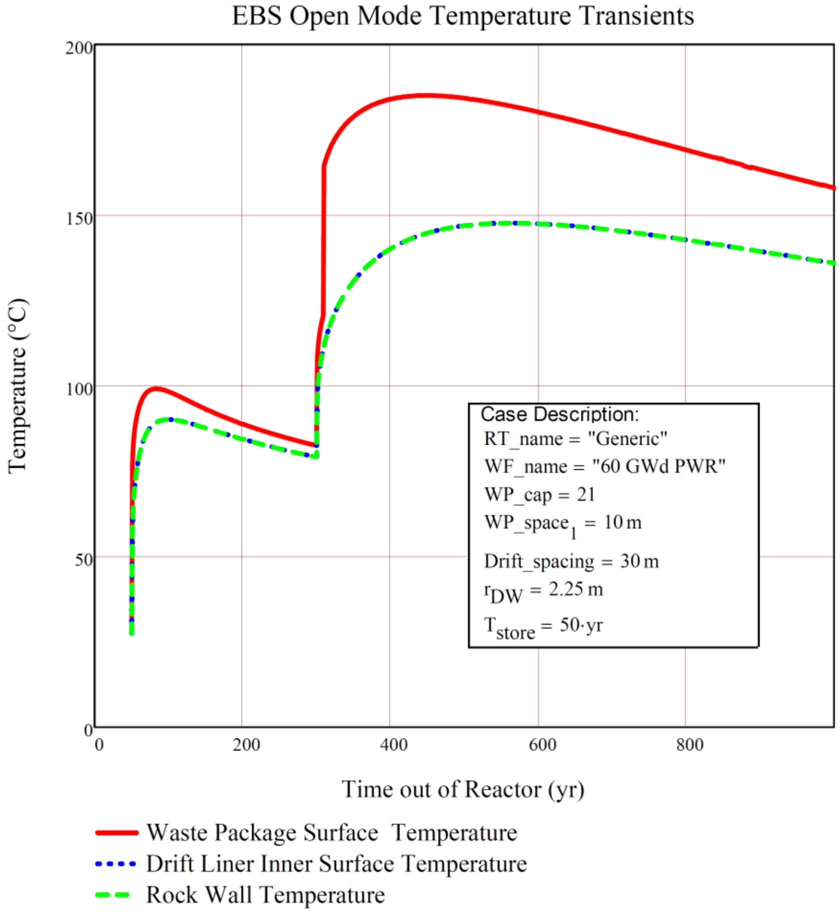


Figure B.3-29 Case 62 – Thermal conductivity of 1 W/m-K and burnup of 60 GWd/MT

WPs are 21 PWR WPs. Repository times are 50 yr storage before ventilation, 250 yr ventilation at 75% efficiency, and 10 yr of non-ventilated backfill installation before closure. Axial and lateral spacings are 10 and 30 m, respectively.



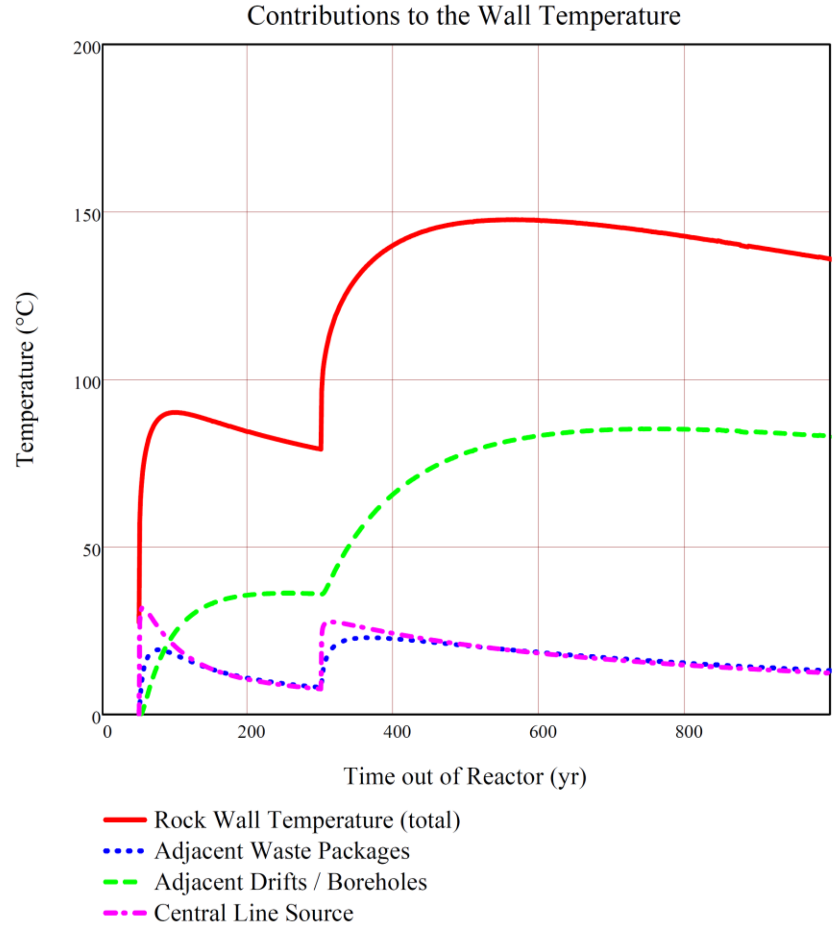


Figure B.3-30 Case 63 – Thermal conductivity of 2 W/m-K and burnup of 60 GWd/MT

See Case 62, Figure B.3-24, for other parameters.

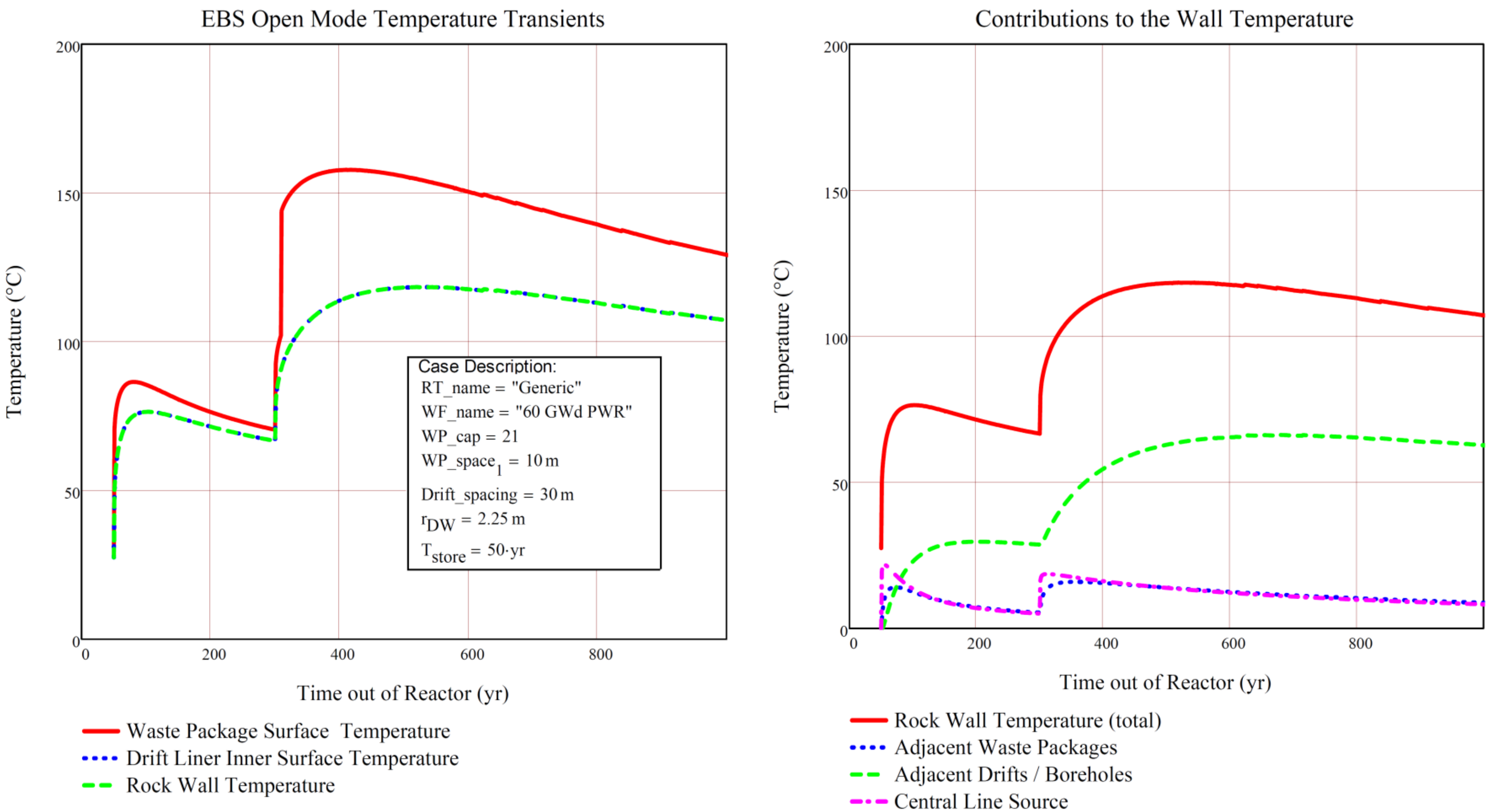
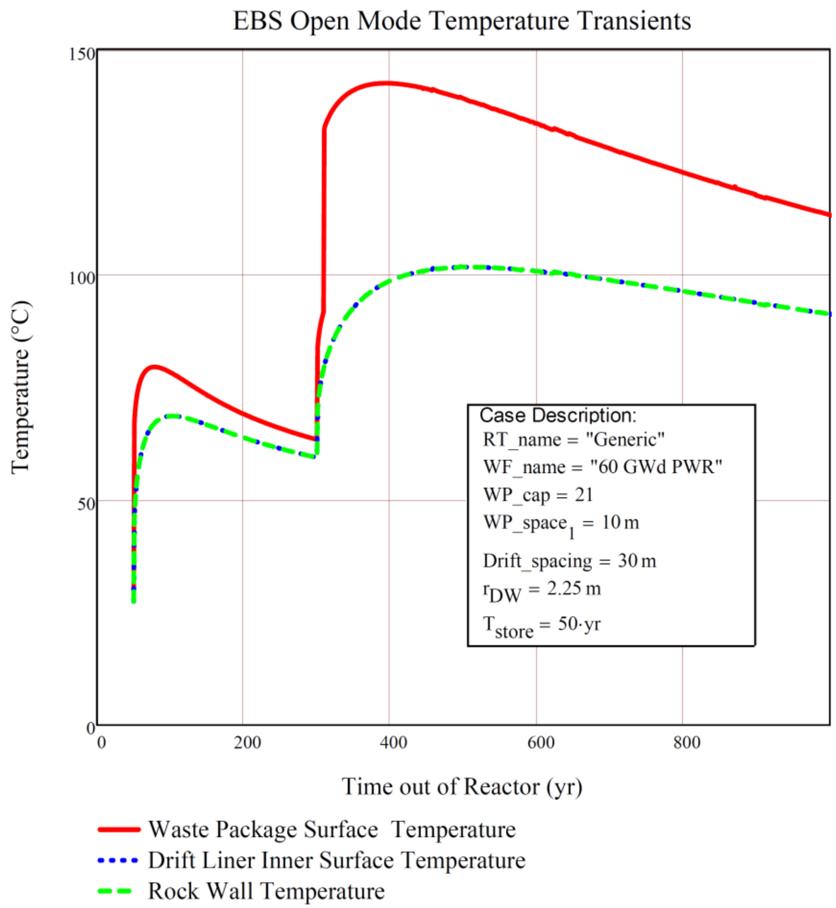


Figure B.3-31 Case 64 – Thermal conductivity of 3 W/m-K and burnup of 60 GWd/MT

See Case 62, Figure B.3-24, for other parameters.



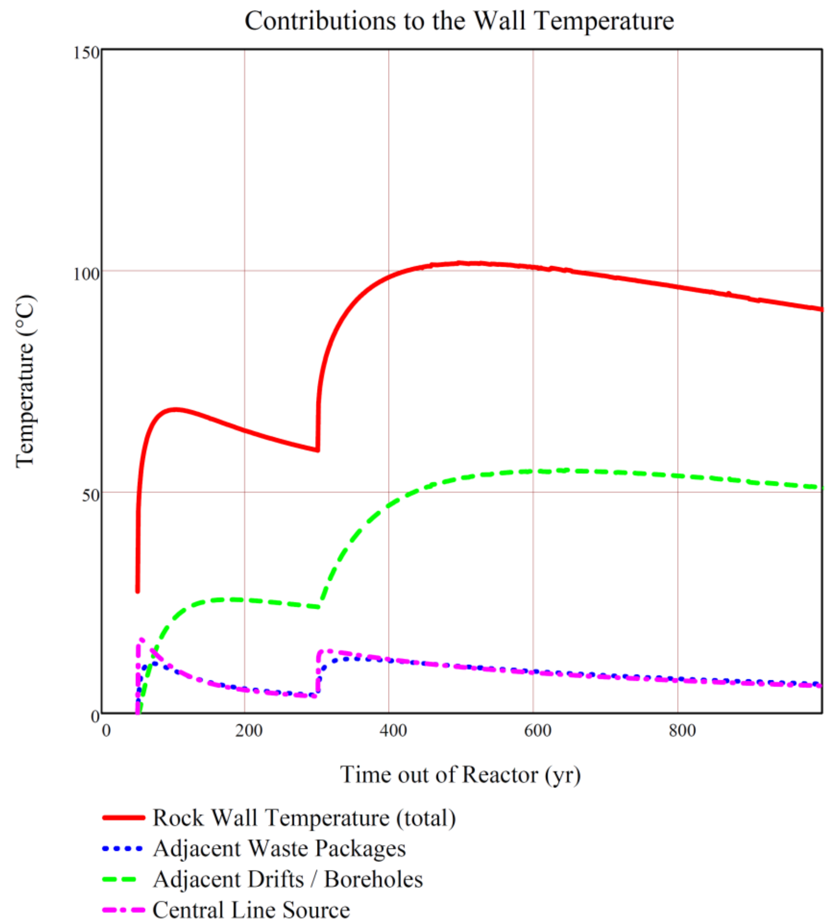


Figure B.3-32 Case 65 – Thermal conductivity of 4 W/m-K and burnup of 60 GWd/MT

See Case 62, Figure B.3-24, for other parameters.

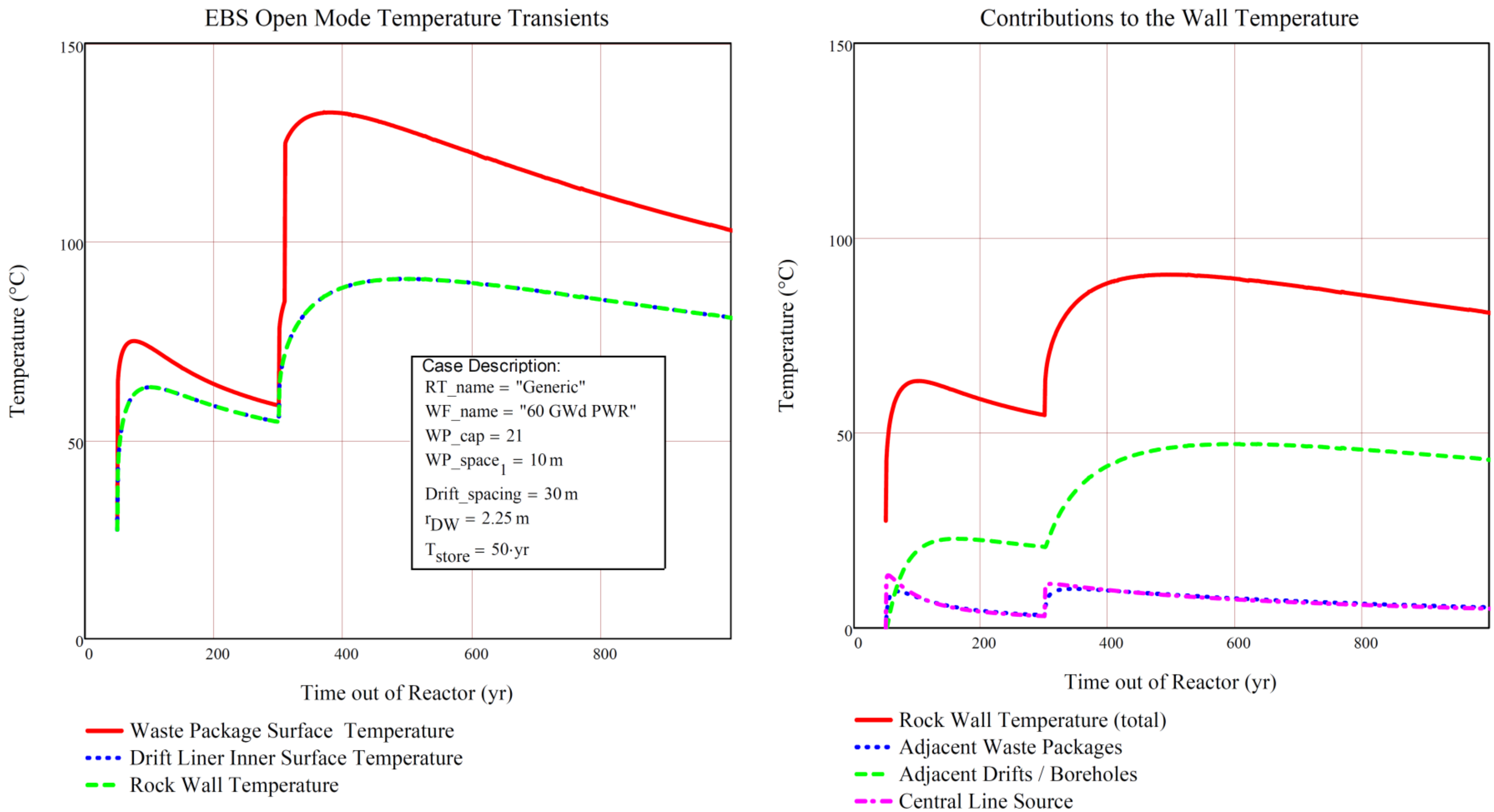


Figure B.3-33 Case 66 – Thermal conductivity of 5 W/m-K and burnup of 60 GWd/MT

See Case 62, Figure B.3-24, for other parameters.

B.3.5 Sensitivity to Generic Backfill Thermal Conductivity

As documented in Section A.4, the base case backfill thermal conductivity is assumed to be 1.2 W/m-K, based on a 70% bentonite / 30% sand mixture. However, the addition of graphite to the mixture has the potential to significantly increase the thermal conductivity. Figure 5 of *Influence of Graphite and Quartz Addition on the Thermo-Physical Properties of Bentonite for Sealing Heat-Generating Radioactive Waste* (Jobmann and Buntebarth 2009), shows that mixtures of 80% bentonite and 20% sand can have thermal a conductivity of around 5 W/m-K.

Thus the potential exists to develop engineered backfill material mixtures with much higher thermal conductivity than the assumed 1.2 W/m-K value expected of a 70% bentonite / 30% quartz sand mixture.

Table B.3-5 shows the results of a sensitivity study assuming a generic backfill material (composition undefined, but potentially a mix of bentonite, sand, and graphite – see Section A.5), with thermal conductivities ranging from 1, 2, 3, 4, and 5 W/m-K. WPs are 21-PWR with 40 GWd/MT burnup. Axial spacing is 10 m and lateral spacing is 30 m.

Table B.3-5 Cases used in the generic backfill thermal conductivity sensitivity study

Figure Number	Case Number	Burnup, GWd/MT	Backfill Thermal Conductivity, W/m-K		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.3-34	67	40	1		134.6	593		170.4	488
B.3-35	68	40	2		134.6	593		151.8	535
B.3-36	69	40	3		134.6	593		145.9	554
B.3-37	70	40	4		134.6	593		143.0	567
B.3-38	71	40	5		134.6	593		141.3	567

See Figure 3.2-6 for a graphic presentation of the results shown in Table B.3-5.

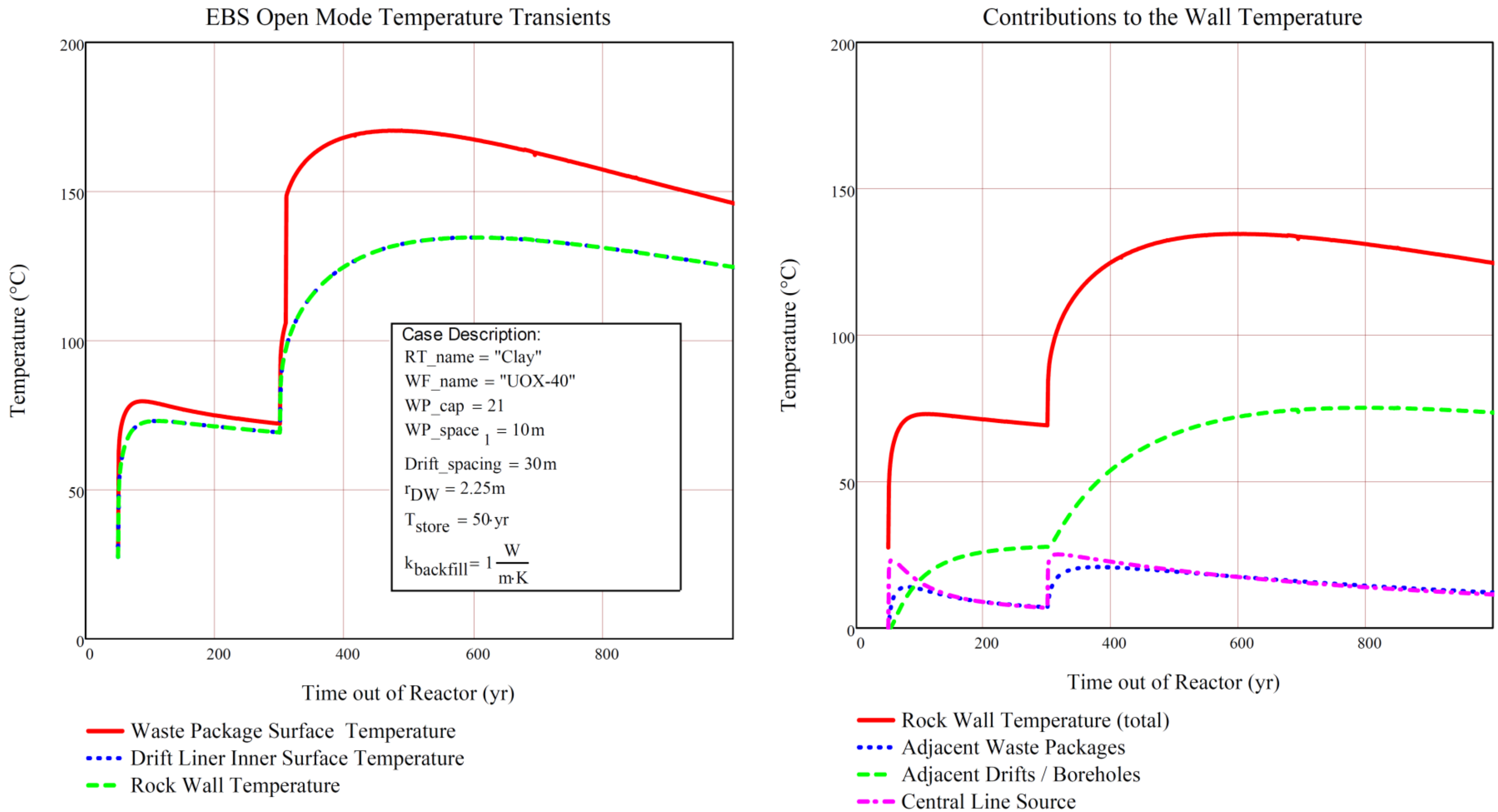


Figure B.3-34 Case 67 – Generic Backfill Thermal conductivity of 1 W/m-K

This case also assumes 21-UOX waste package with 40 GWd/MT burnup and other parameters of Case 21.

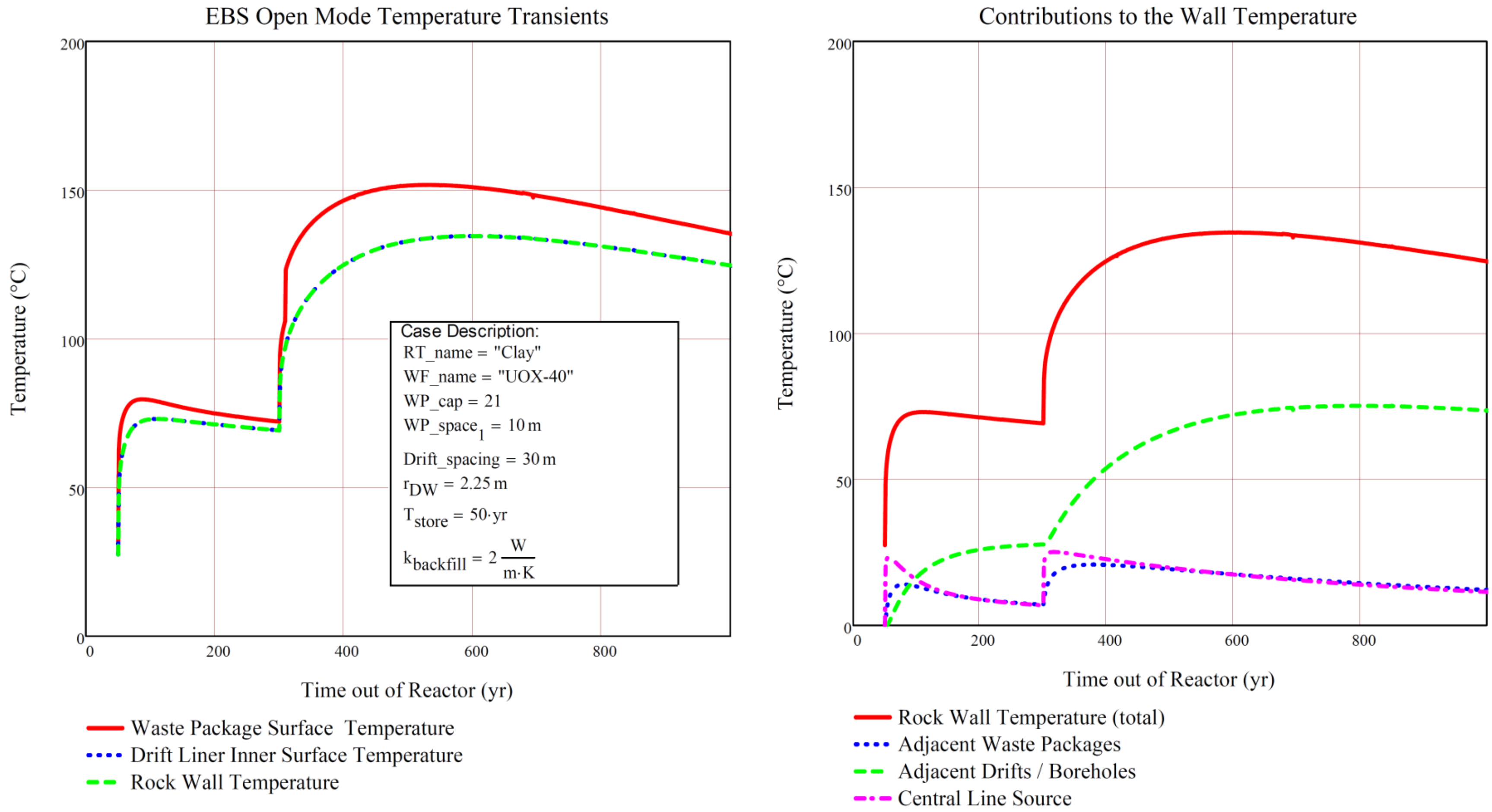


Figure B.3-35 Case 68 – Generic Backfill Thermal conductivity of 2 W/m-K

This case also assumes 21-UOX waste package with 40 GWd/MT burnup and other parameters of Case 21.

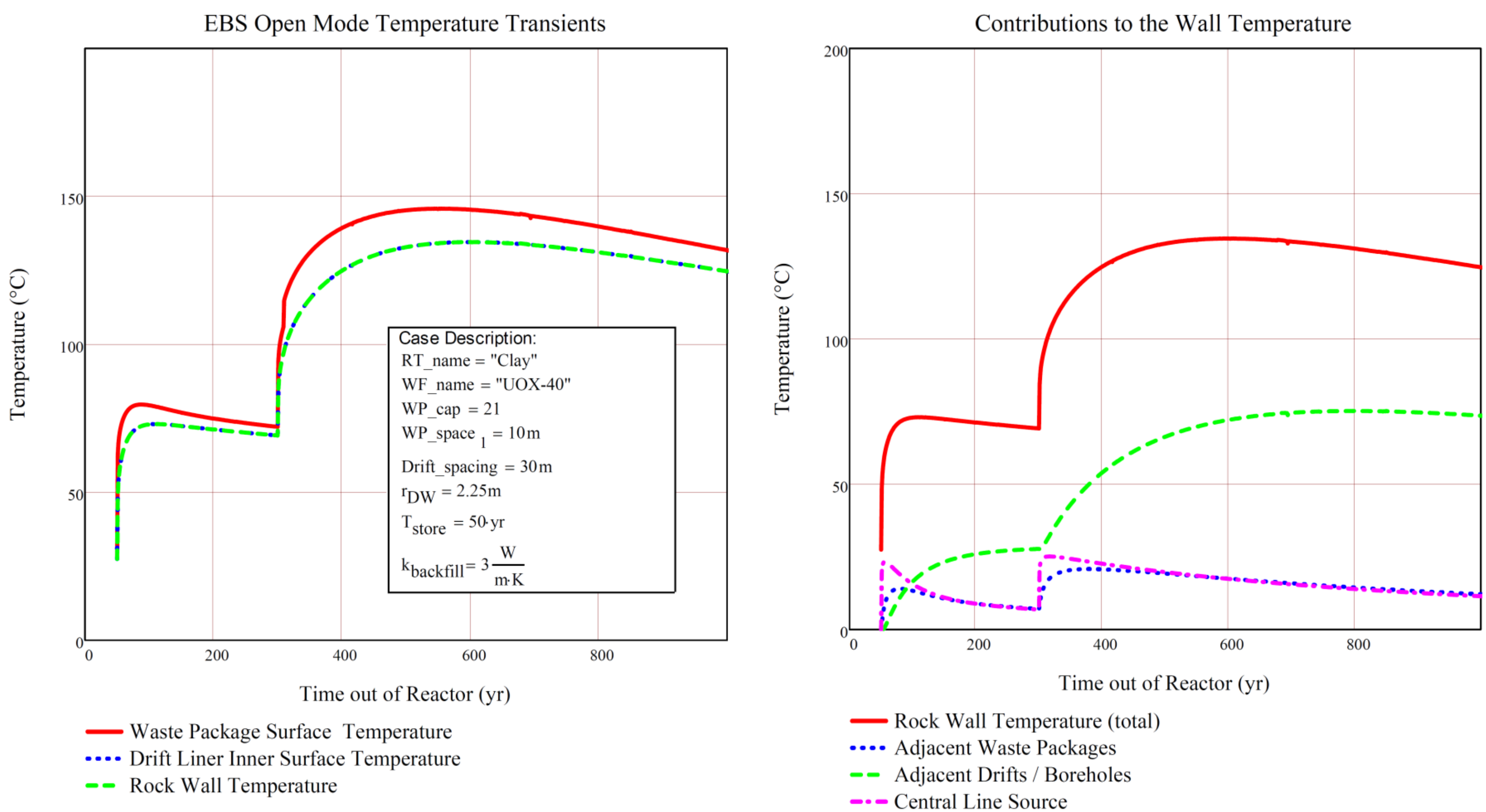


Figure B.3-36 Case 69 – Generic Backfill Thermal conductivity of 3 W/m-K

This case also assumes 21-UOX waste package with 40 GWd/MT burnup and other parameters of Case 21.

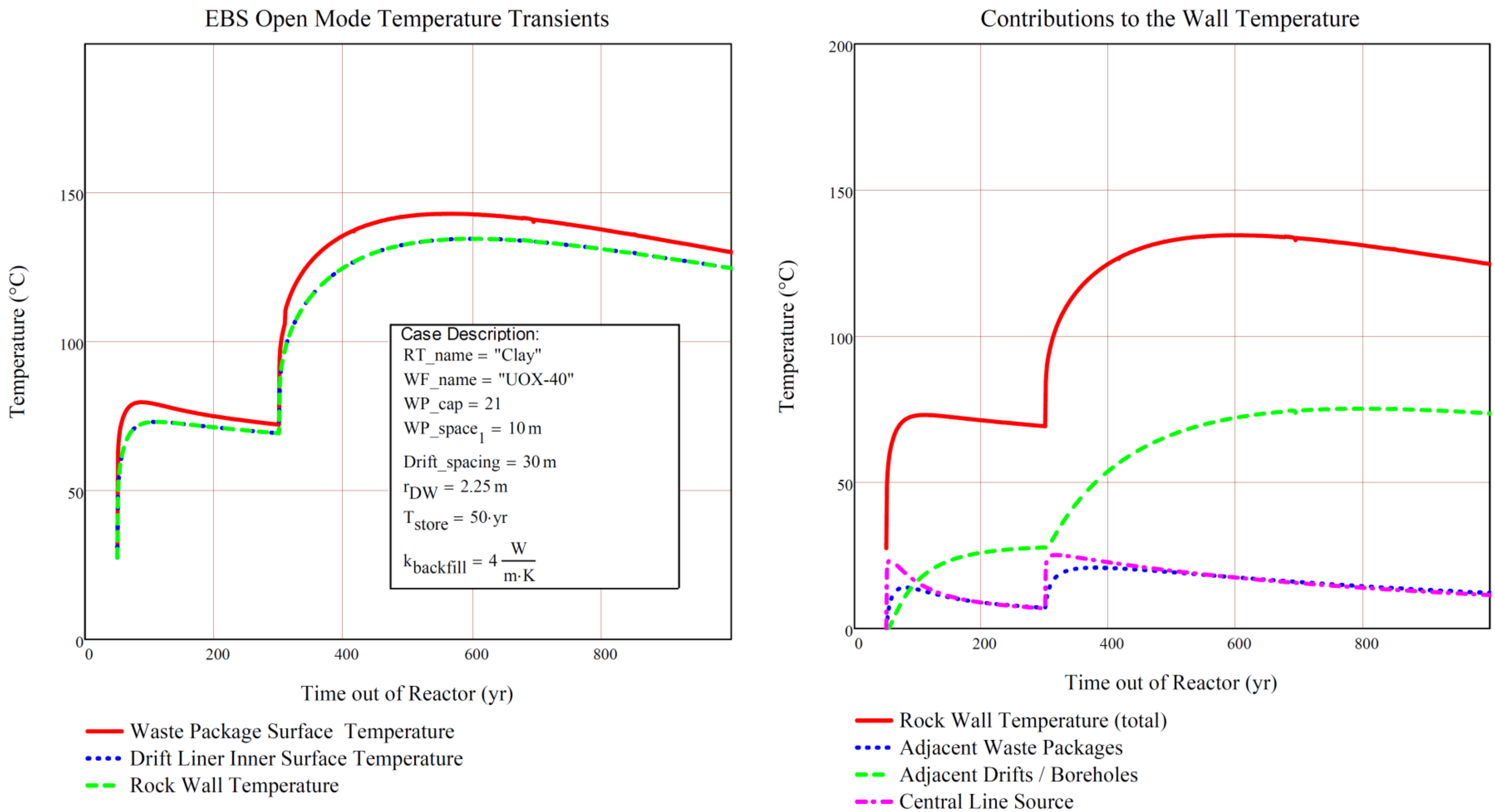
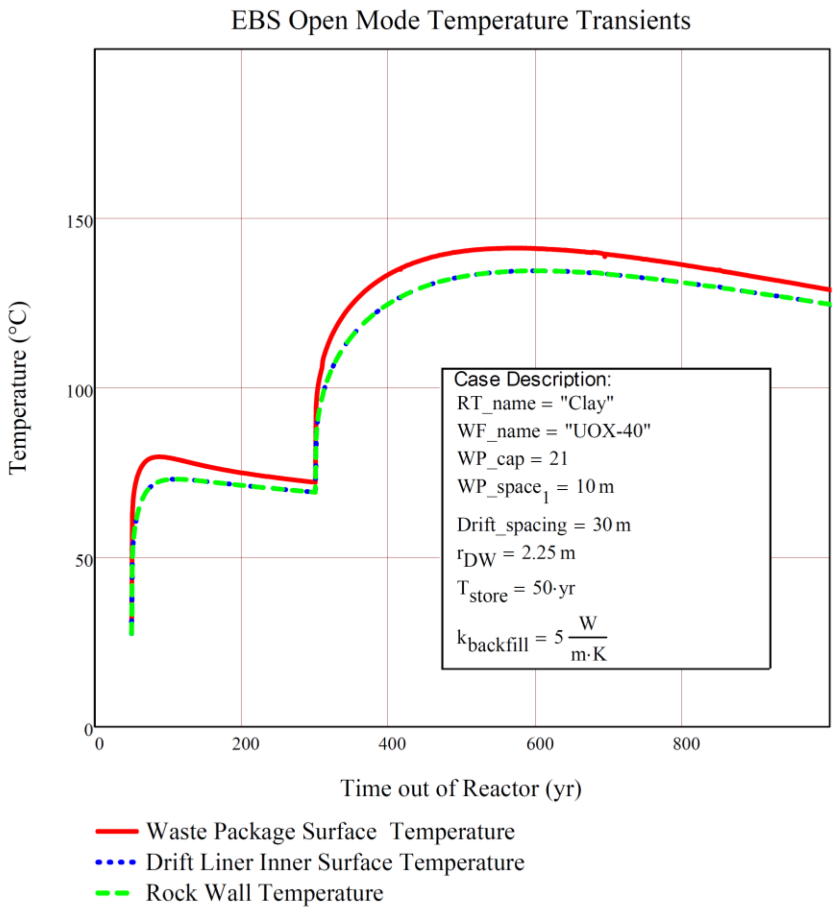


Figure B.3-37 Case 70 – Generic Backfill Thermal conductivity of 4 W/m-K

This case also assumes 21-UOX waste package with 40 GWd/MT burnup and other parameters of Case 21.



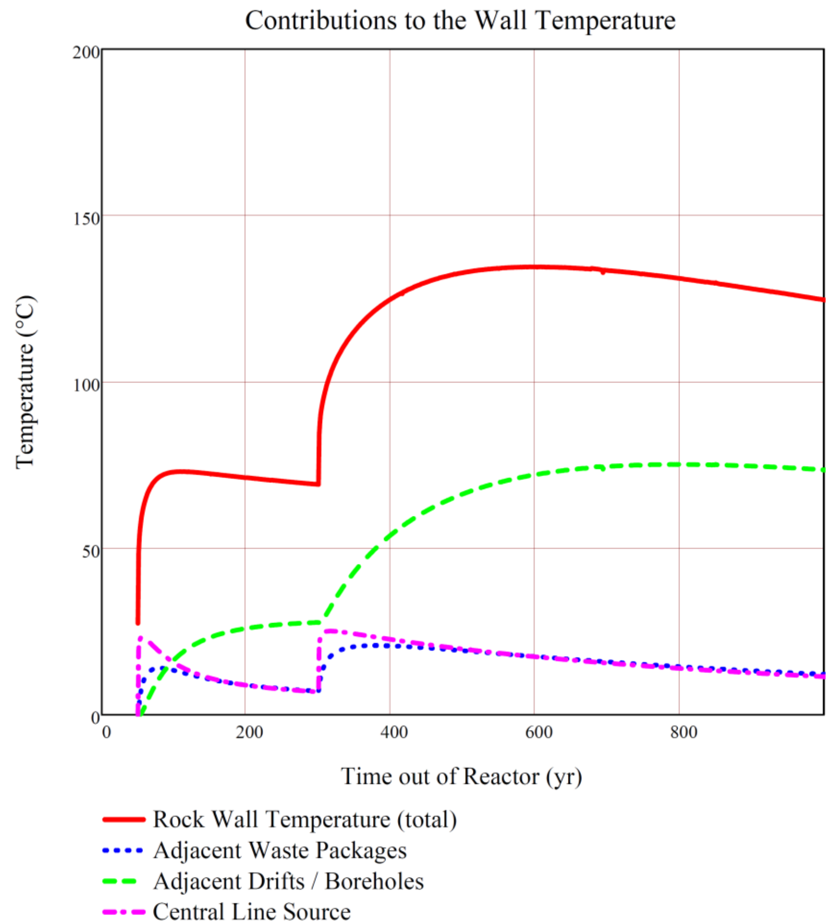


Figure B.3-38 Case 71 – Generic Backfill Thermal conductivity of 5 W/m-K

This case also assumes 21-UOX waste package with 40 GWd/MT burnup and other parameters of Case 21.

B.4 Uncertainty in Host Rock Thermal Conductivity

One and two standard deviations in thermal conductivity were calculated for clay and alluvium using the data shown in Figure 3.1-4. The ranges in the published data include three factors: variation from site to site, variation at a particular site, and uncertainty in the measurements themselves. It is normally prudent to look at the sensitivity of dependent variables (such as peak temperatures for a given repository design) using ± 2 standard deviations in the independent variables. However, because sites with very low thermal conductivities may be excluded, depending on the details of the waste stream and the repository design, considering the range of peak temperatures using ± 1 standard deviation may be more appropriate.

These calculations use 50 yr storage time, 250 yr ventilation at 75% efficiency, and 10 yr backfill installation time. Axial and lateral spacings are 10 and 30 m, respectively. WPs are 21-PWR with 40 GWd/MT burnup.

Table B.4-1 Uncertainty analysis for rock thermal conductivity and rock thermal diffusivity (± 1 and ± 2 std. dev.) in clay and alluvium

The thermal diffusivity range for each medium only includes the uncertainty in conductivity range; the volumetric heat capacity is the nominal value for the medium. These calculations use 50 yr storage time, 250 yr ventilation at 75% efficiency, and 10 yr backfill installation time. Axial and lateral spacings are 10 and 30 m, respectively. WPs are 21-PWR with 40 GWd/MT burnup.

Figure Number	Case Number	Medium	# of standard deviations from the mean	Thermal Conductivity (W/m-K)	Thermal Diffusivity (m^2/sec)		Peak Rock Temp, °C	Peak Time, yr		Peak WP Surface Temp, °C	Peak Time, yr
B.4-1	21m	Clay	-2	0.51	1.90E-07		265.2	675		291.2	593
B.4-2	21r	Clay	-1	1.12	4.18E-07		172.1	648		200.0	536
B.4-3	**21**	**Clay**	**Mean**	**1.73**	**6.45E-07**		134.6	593		164.1	488
B.4-4	21s	Clay	+1	2.34	8.72E-07		115.6	592		146.2	464
B.4-5	21n	Clay	+2	2.95	1.10E-06		102.5	567		133.9	442
B.4-6	49a	Alluvium	-2	0.84	5.45E-07		238.5	611		266.5	544
B.4-7	49c	Alluvium	-1	0.95	6.17E-07		222.0	606		250.5	515
B.4-8	**49**	**Alluvium**	**Mean**	**1.06**	**6.88E-07**		201.5	593		230.3	521
B.4-9	49d	Alluvium	+1	1.17	7.59E-07		196.3	592		225.4	521
B.4-10	49b	Alluvium	+2	1.28	8.31E-07		186.2	592		215.6	515

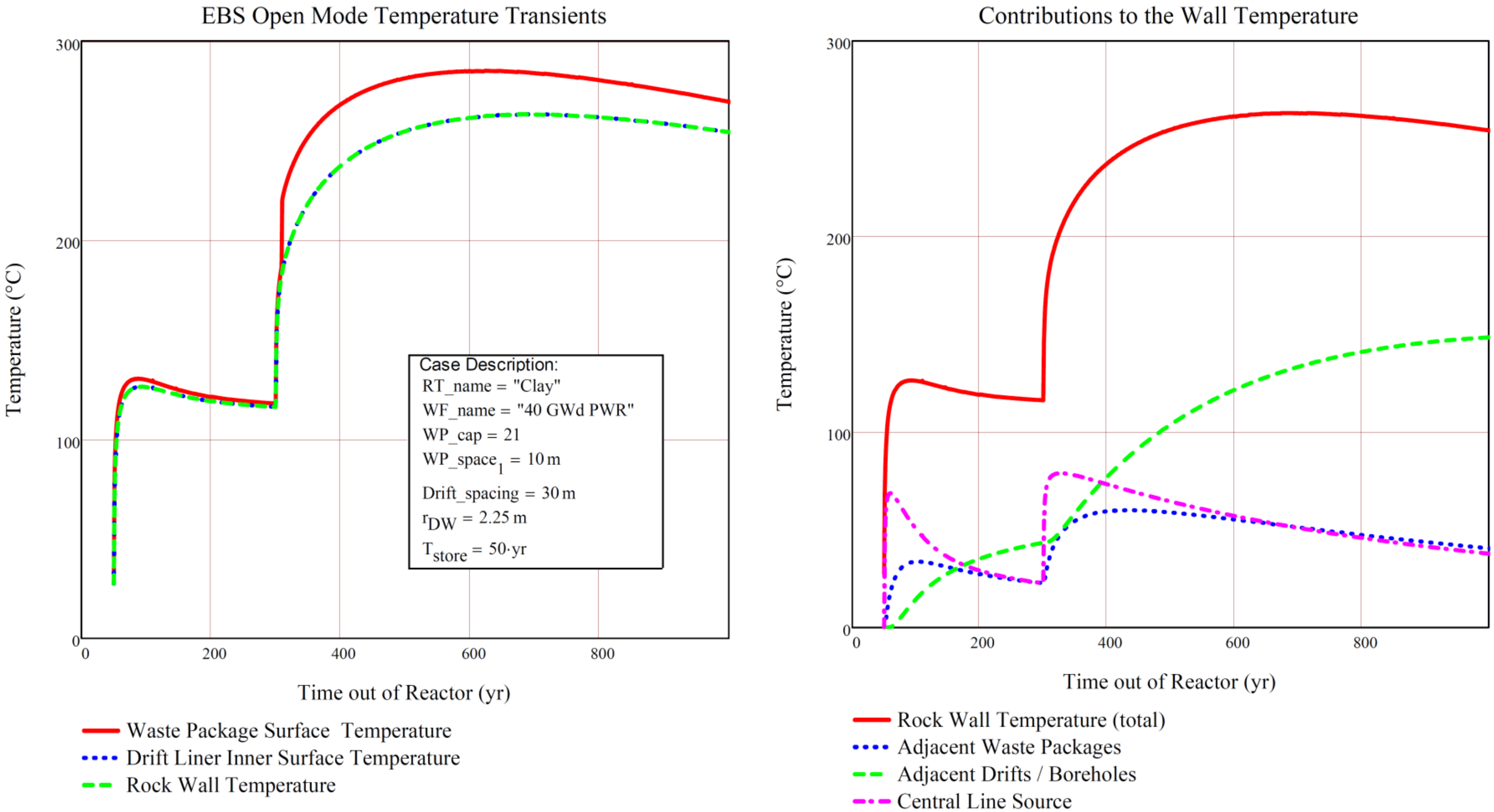


Figure B.4-1 Case 21m – Thermal conductivity 2 standard deviations below the mean for a clay repository

For other parameters, see Base Case 21, Figure B.4-3.

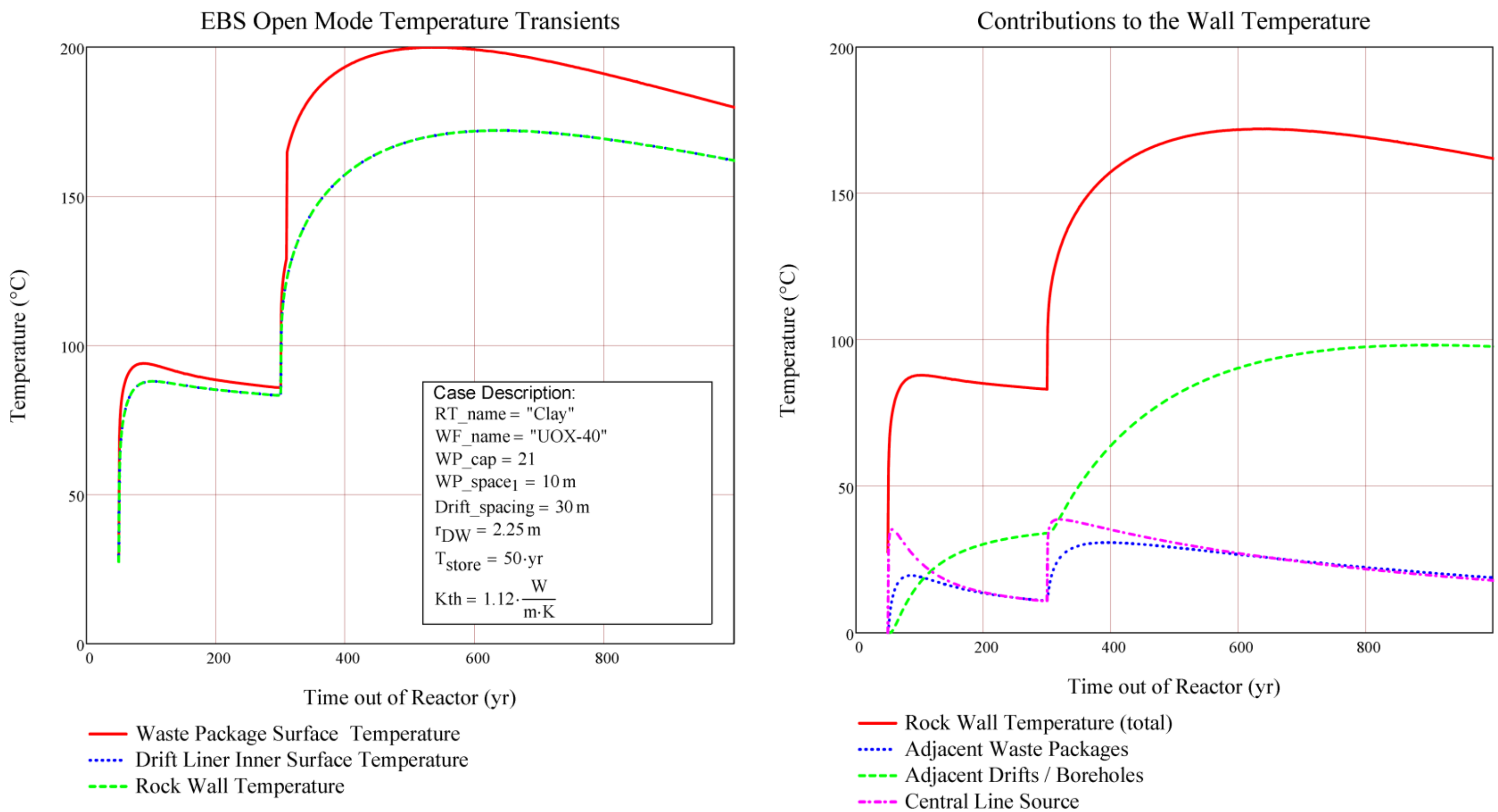


Figure B.4-2 Case 21r – Thermal conductivity 1 standard deviation below the mean for a clay repository

For other parameters, see Base Case 21, Figure B.4-3.

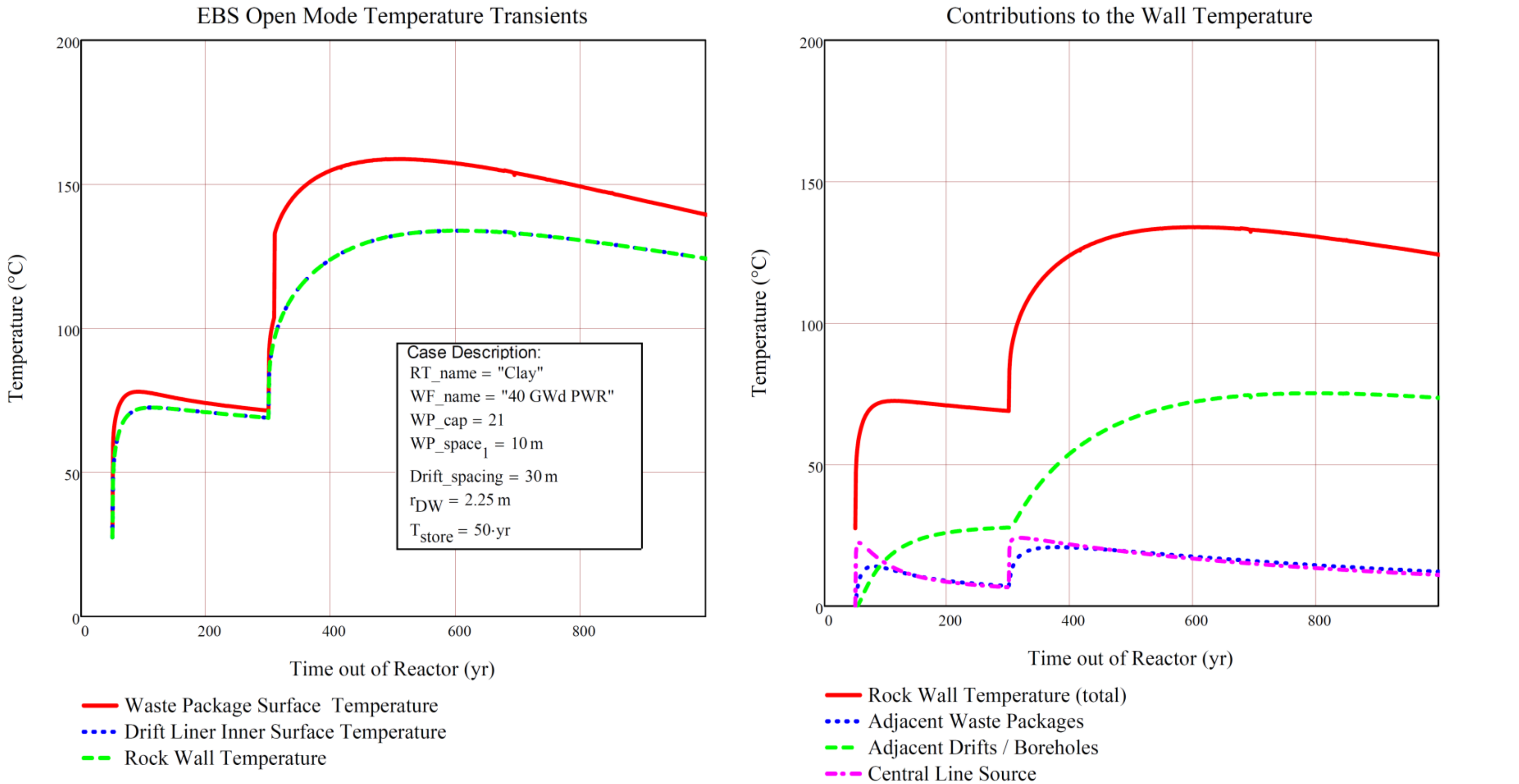


Figure B.4-3 Case 21 – Thermal conductivity is the mean for a clay repository. This is the base case for clay

The mean volumetric heat capacity is used. WPs are 21-PWR with burnup of 60 GWd/MT. Repository times are 50 yr storage before ventilation, 250 yr ventilation at 75% efficiency, and 10 yr of non-ventilated backfill installation before closure. Axial and lateral spacings are 10 and 30 m, respectively. This is a duplicate of Figure B.2-9.

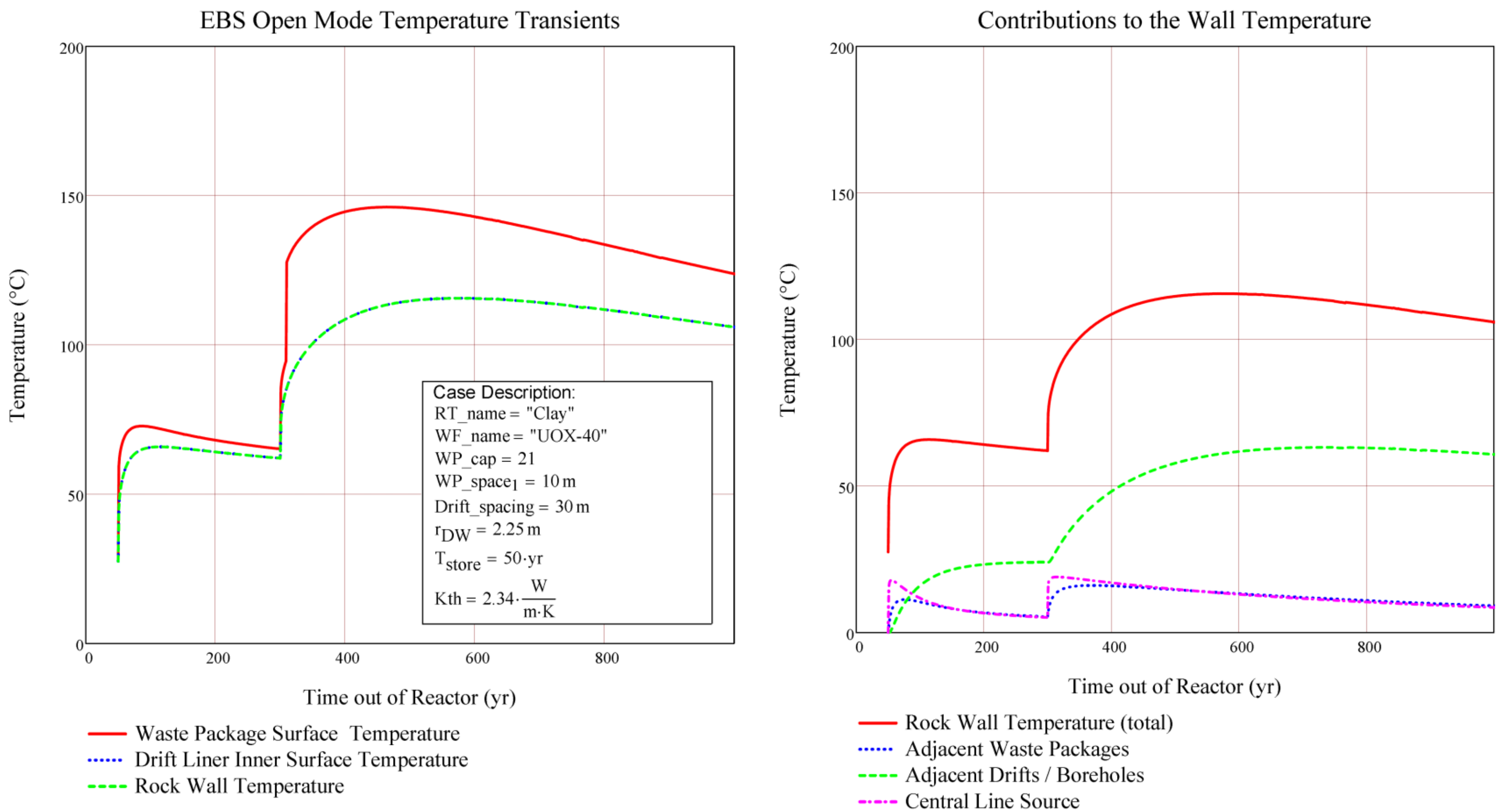


Figure B.4-4 Case 21s – Thermal conductivity 1 standard deviation above the mean for a clay repository

For other parameters, see Base Case 21, Figure B.4-3.

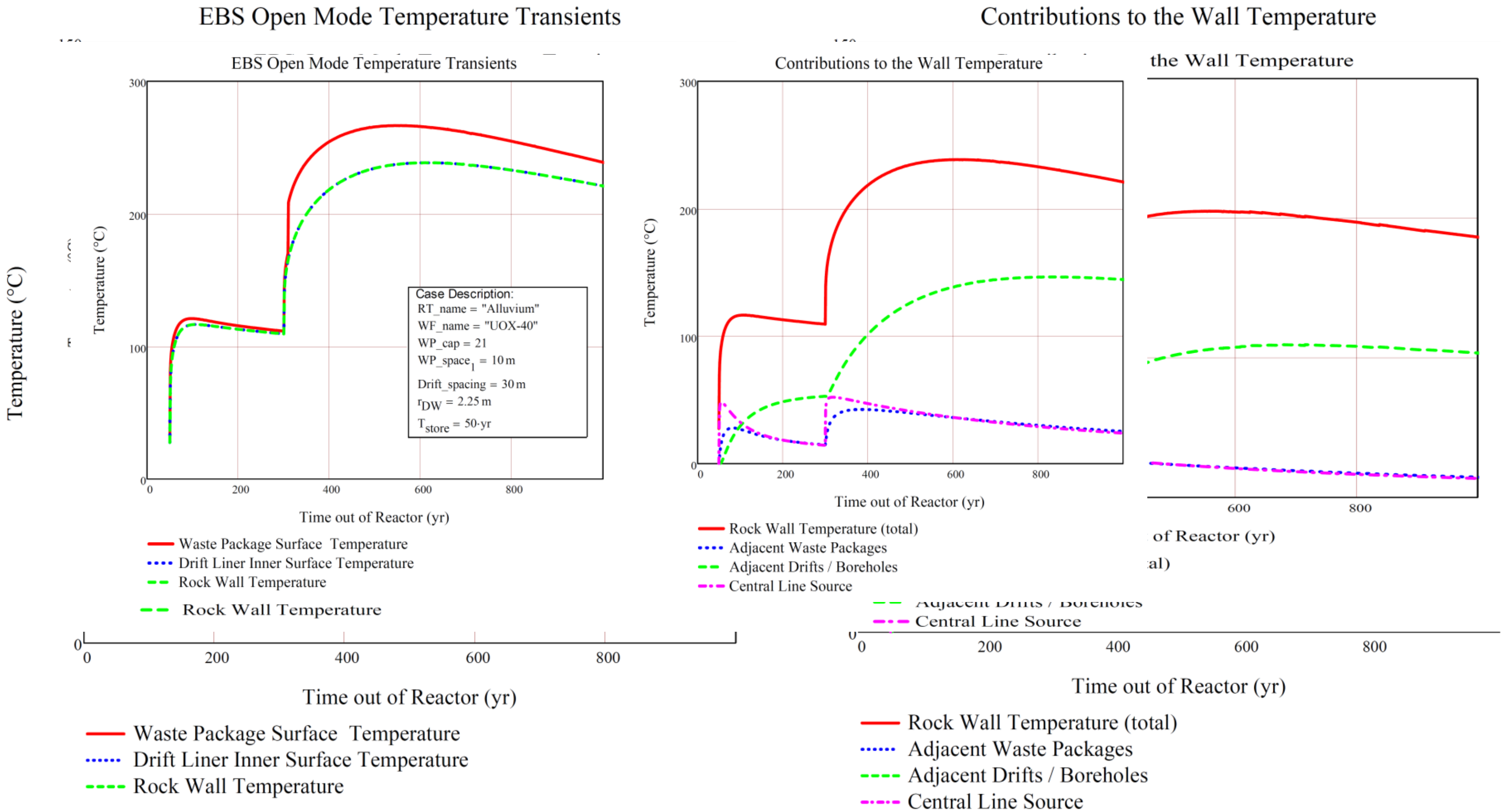
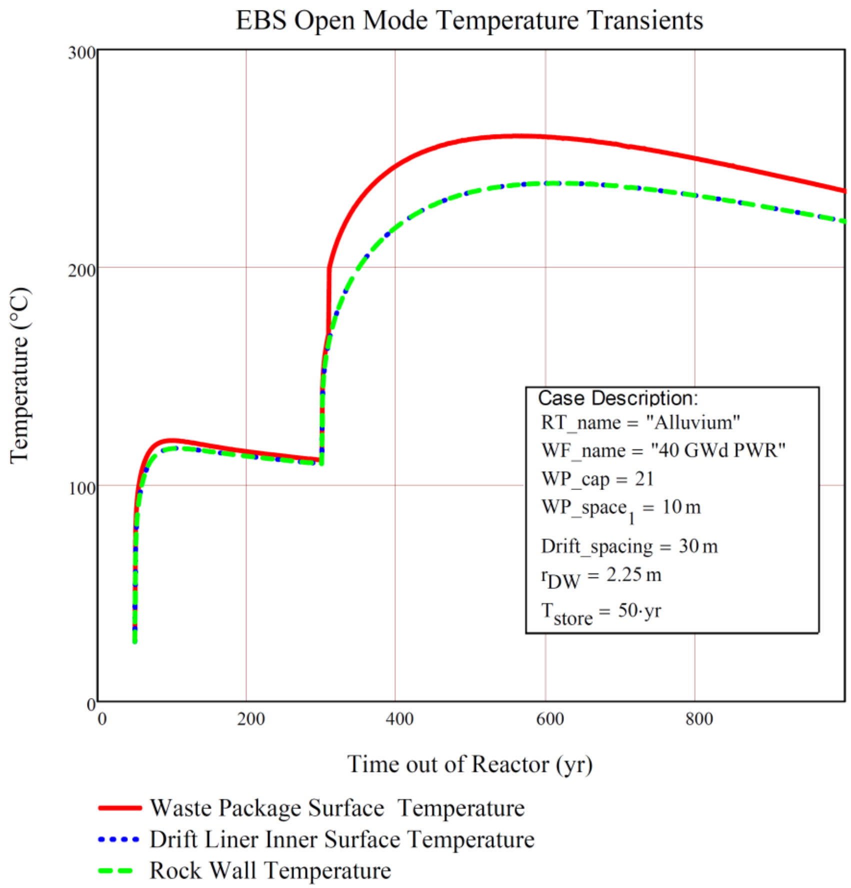


Figure B.4-5 Case 21n – Thermal conductivity 2 standard deviations above the mean for a clay repository

For other parameters, see Base Case 21, Figure B.4-3.



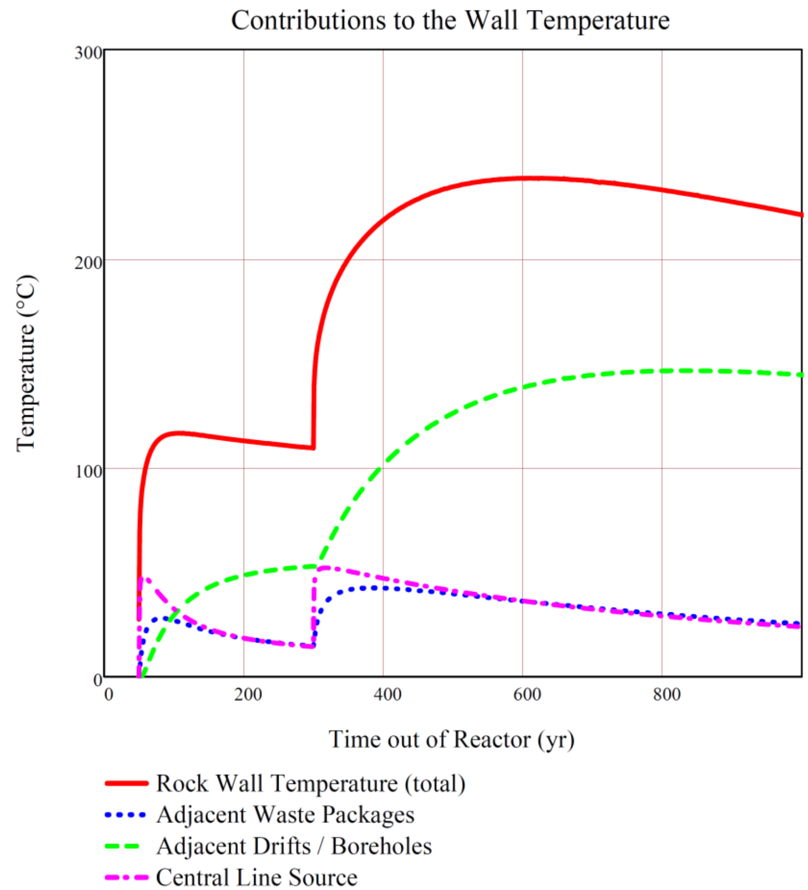


Figure B.4-6 Case 49a – Thermal conductivity 2 standard deviations below the mean for an alluvium repository

For other parameters, see Base Case 49, Figure B.4-8.

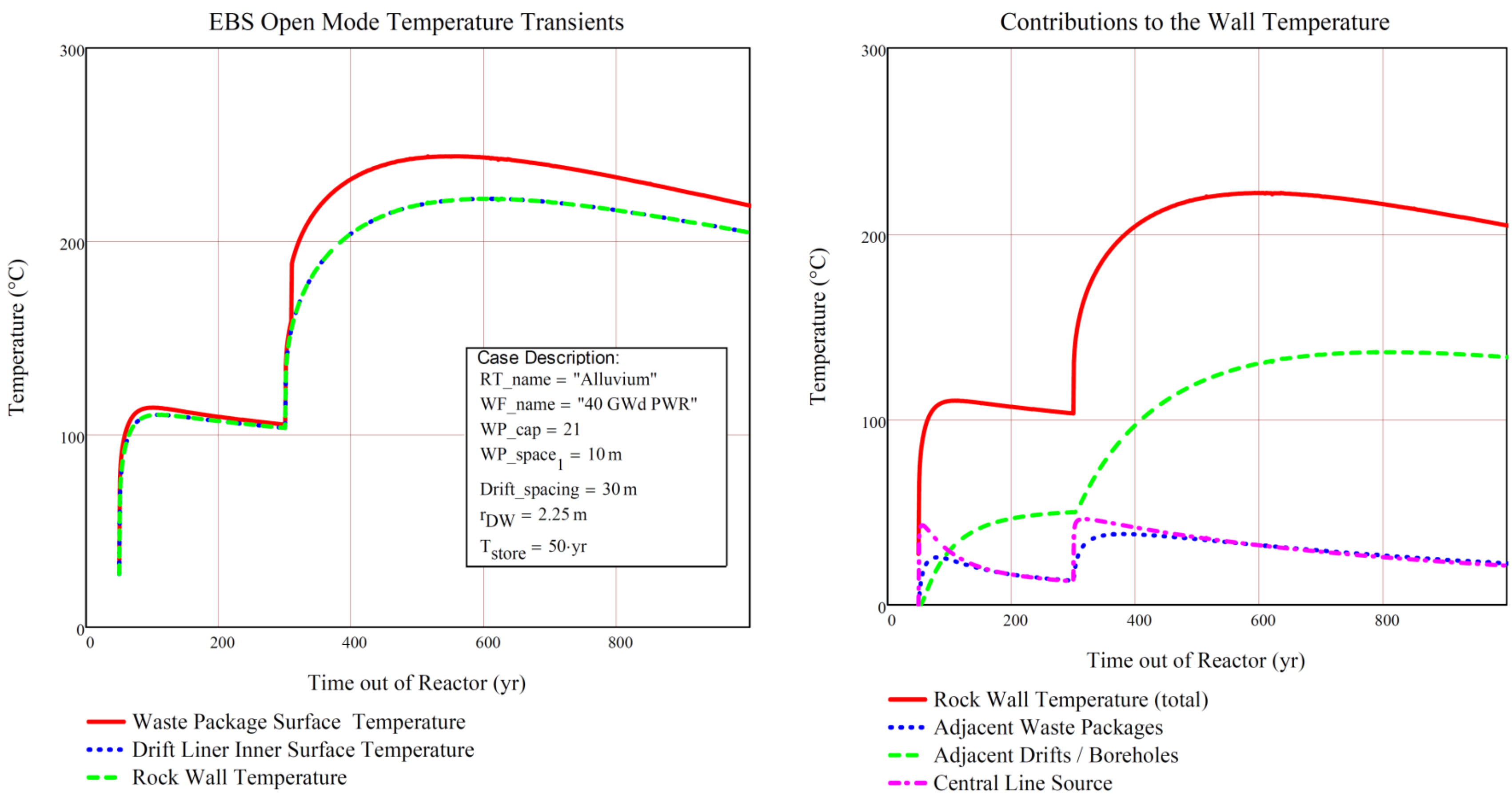


Figure B.4-7 Case 49c – Thermal conductivity 1 standard deviation below the mean for an alluvium repository

For other parameters, see Base Case 49, Figure B.4-8.

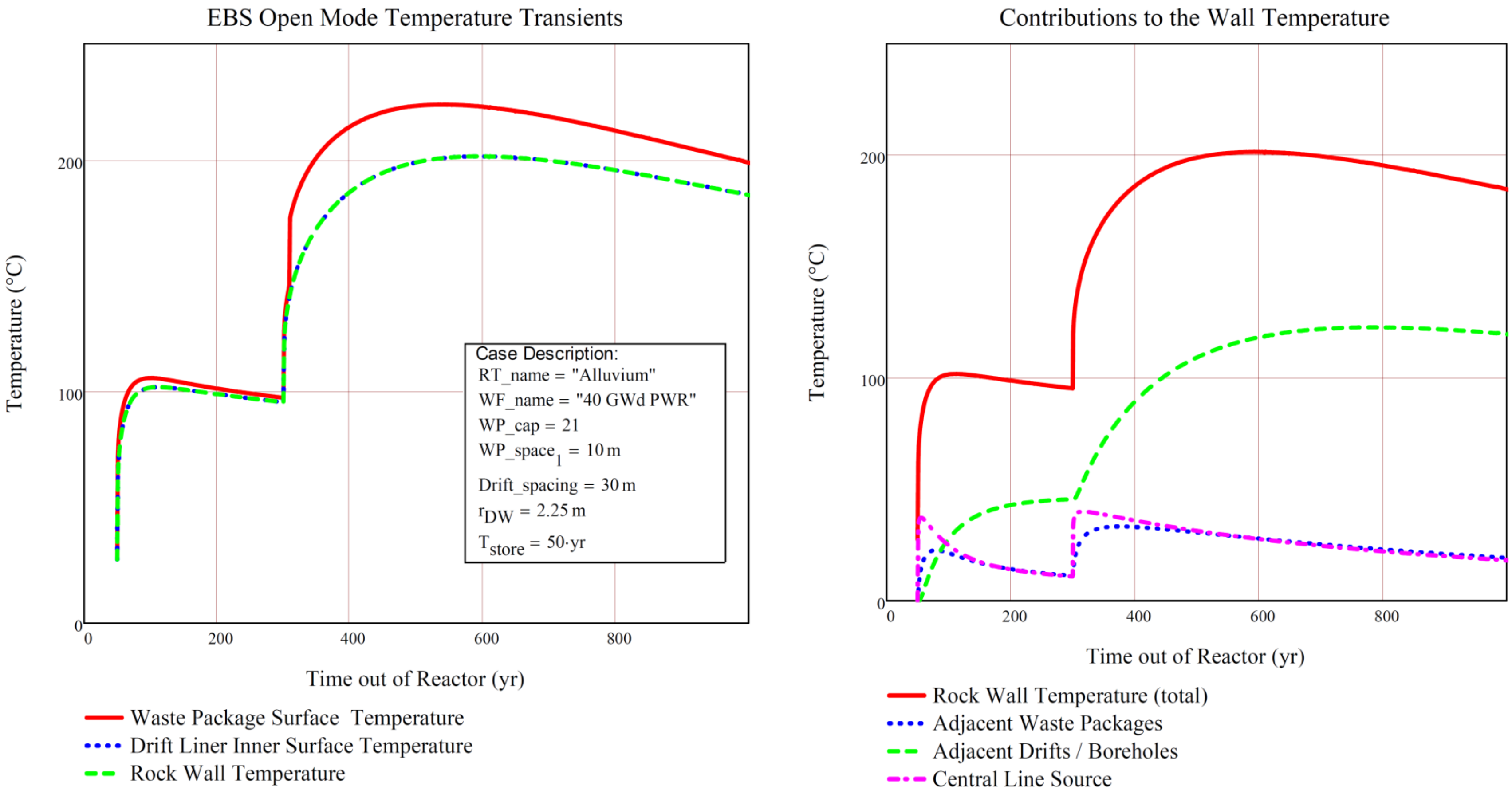


Figure B.4-8 Case 49 – Thermal conductivity is the mean for an alluvium repository

The mean volumetric heat capacity is used. WPs are 21-PWR with burnup of 60 GWd/MT. Repository times are 50 yr storage before ventilation, 250 yr ventilation at 75% efficiency, and 10 yr of non-ventilated backfill installation before closure. Axial and lateral spacings are 10 and 30 m, respectively. This is a duplicate of Figure B.2-25.

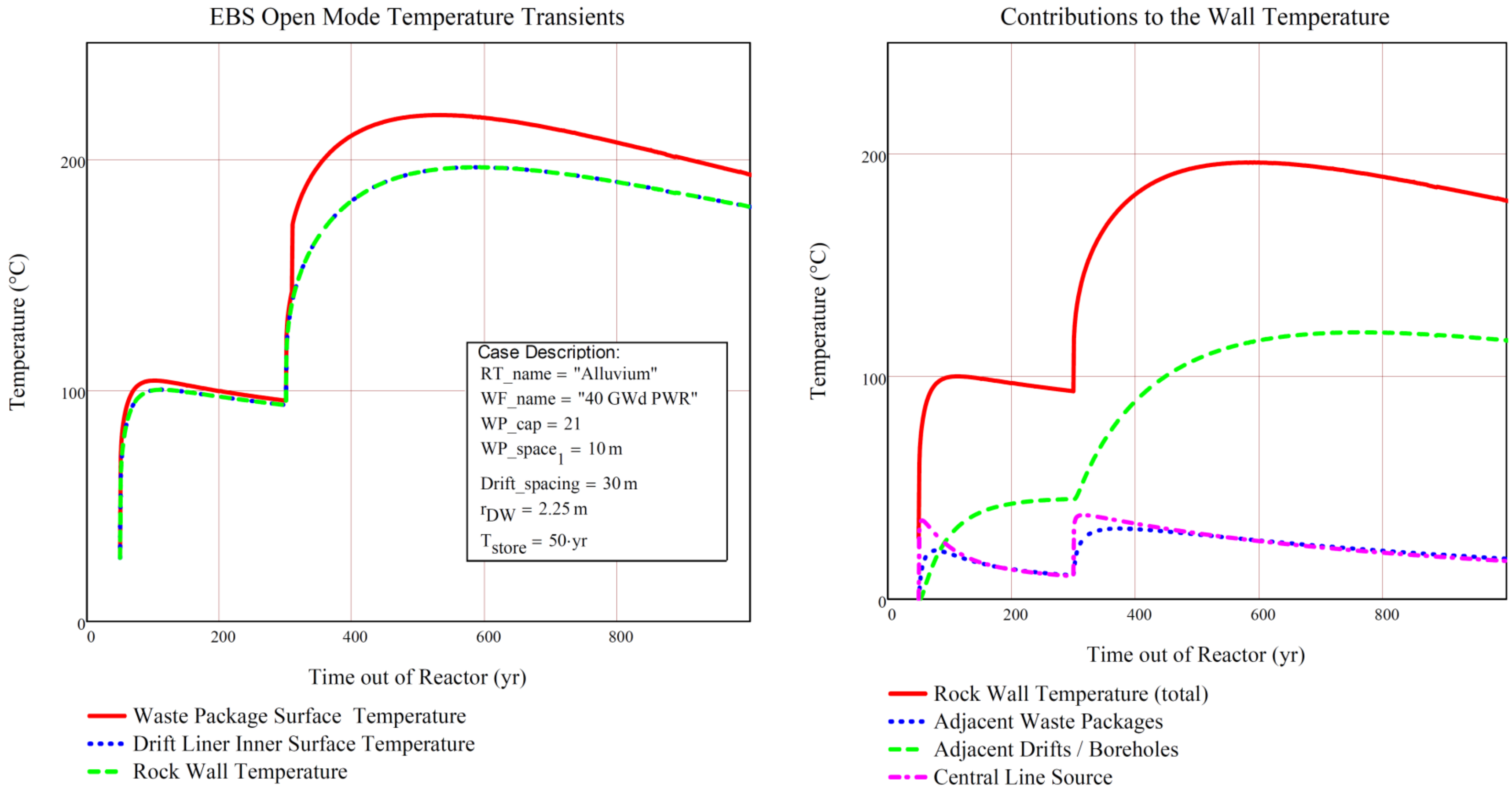


Figure B.4-9 Case 49d – Thermal conductivity 1 standard deviation above the mean for an alluvium repository

For other parameters, see Base Case 49, Figure B.4-8.

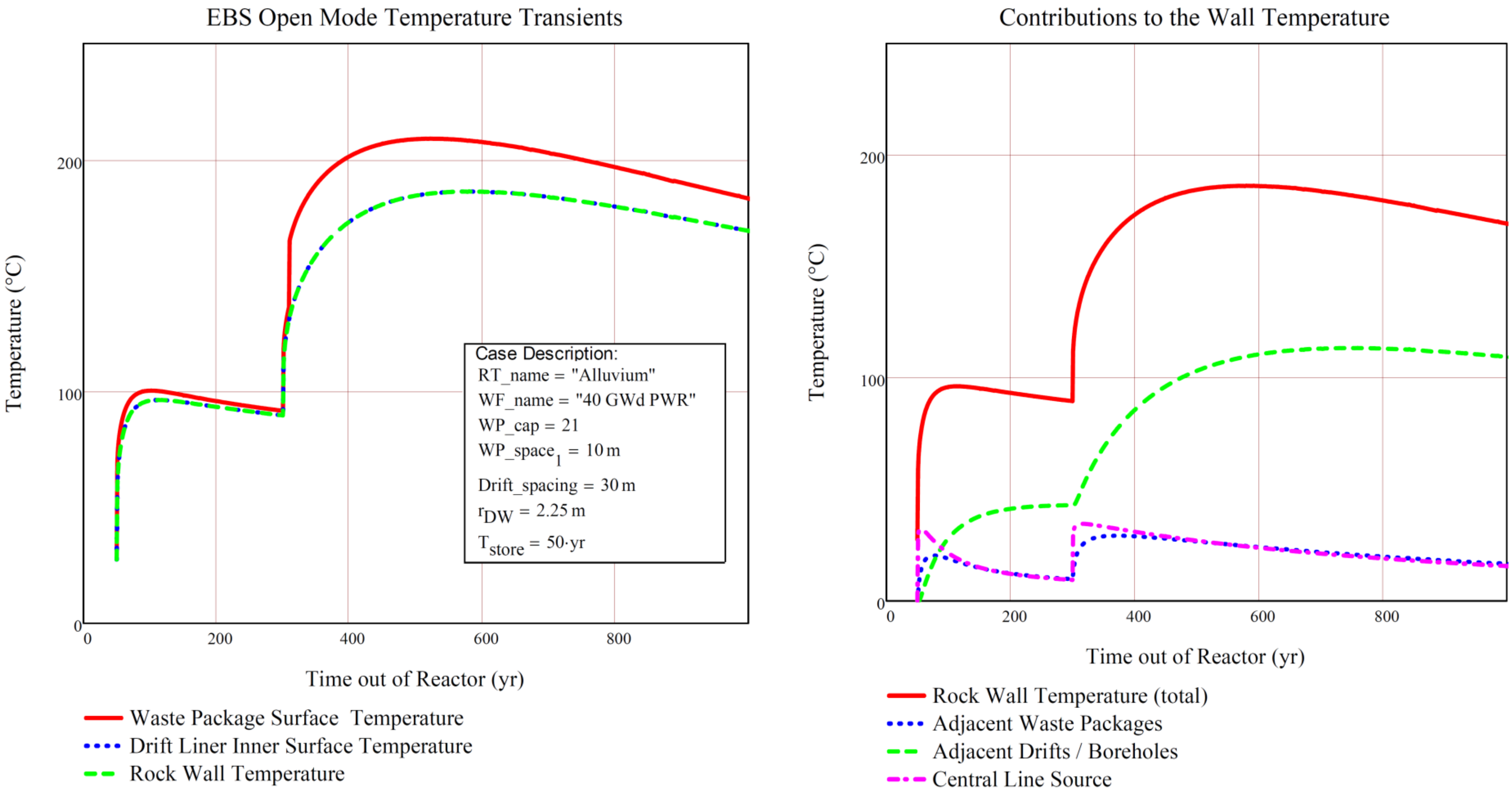


Figure B.4-10 Case 49b – Thermal conductivity 2 standard deviations above the mean for an alluvium repository

For other parameters, see Base Case 49, Figure B.4-8.

B.5 Design Test Case

Using the insight gained by the base case analyses and the sensitivity studies presented in earlier sections of Appendix B and Section 3.2, a combination of parameters was selected to examine a repository design and operational case for disposal of 21-UOX waste packages. These calculations use 50 yr storage time, and either 50 or 100 years of ventilation at 75% efficiency, and 10 yr backfill installation time.

Table B.5-1 Design test case - drift spacing = 60 m, 21-UOX, 40 GWd/MT, with 50 and 100 years of ventilation, and varying backfill thermal conductivity

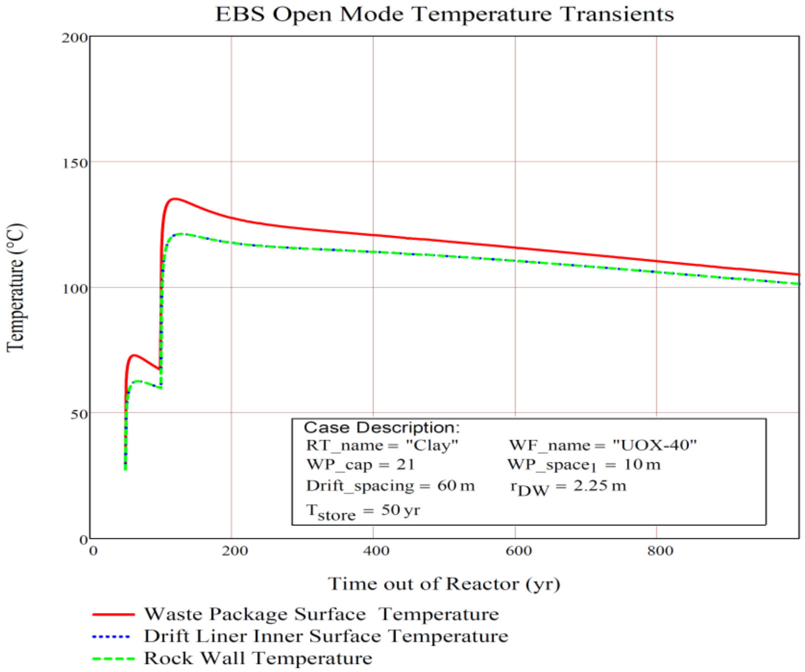
Figure Number	Case Number	Media	Burnup (GWd/MT)	Case Description	T_{store} (yr)	$T_{operate}$ (=T_{store}+T_{vent}) (yr)	Peak Rock Temp, C	Peak Time, yr	Peak WP Surface Temp, C	Peak Time, yr
B.5-1	72	Clay	40	No backfill	50	100	119.4	129	131.4	121
B.5-2	73	Clay	40	backfill kth=2	50	100	119.4	129	162.7	113
B.5-3	73b	Clay	40	backfill kth=1.2	50	100	119.4	129	193.5	110
B.5-4	73a	Clay	40	backfill kth=0.6	50	100	119.4	129	271.3	110
B.5-5	74	Clay	40	r_{DW} = 5.25 m	50	100	100.8	470	**	**
B.5-6	75	Clay	40	No backfill	50	150	106.4	384	113.2	241
B.5-7	76	Clay	40	backfill kth=2	50	150	106.4	384	132.2	177
B.5-8	76b	Clay	40	backfill kth=1.2	50	150	106.4	384	153.2	168
B.5-9	76a	Clay	40	backfill kth=0.6	50	150	106.4	384	208.2	161
B.5-10	77	Clay	40	r_{DW} = 5.25 m	50	150	95.0	562	**	**

** Note that the host rock temperature transient at 3 m depth is independent of the EBS design configuration in the model.

Table B.5-2 presents the results for the design test case combining data from 3 different runs - for waste package temperature, and rock wall temperature as a function of waste package spacing (10, 15, and 20 m) with Drift spacing = 60 m, 21-UOX, 40 GWd/MT, Veff=75%, 10 years to backfill, backfill kth = 1.2 W/m-K. The transient results for these cases are presented in Figure 3.3-2, with individual case transients presented in this section of Appendix B.

Table B.5-2 Design Test Case - drift spacing = 60 m, 21-UOX, 40 GWd/MT, with 50 and 100 years of ventilation, and backfill thermal conductivity = 1.2 kW/m-K, and waste package spacing = 10, 15, and 20 m

Figure Number	Case Number	Media	Waste Package Spacing, m	Backfill Thermal kth W/m-K	T_{store} (yr)	$T_{operate}$ (=T_{store}+T_{vent}) (yr)	Peak Rock Temp, C	Peak Time, yr	Peak WP Surface Temp, C	Peak Time, yr
B.5-3	73b	Clay	10	1.2	50	100	119.4	129	193.5	110
B.5-11	73d	Clay	15	1.2	50	100	99.7	125	175.8	110
B.5-12	73c	Clay	20	1.2	50	100	90.9	117	168.2	110



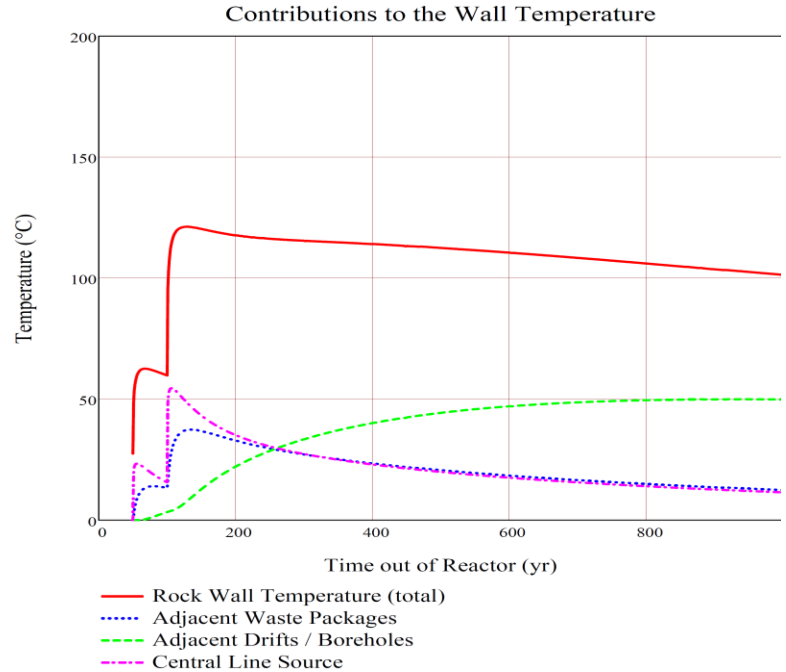


Figure B.5-1 Case 72 –No backfill, 60 m drift/borehole spacing, 50 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

Note: backfill not added until after 1000 years for closure, even though the thermal conductivity is listed on graph

For other parameters, see Base Case 21, Figure B.2-9

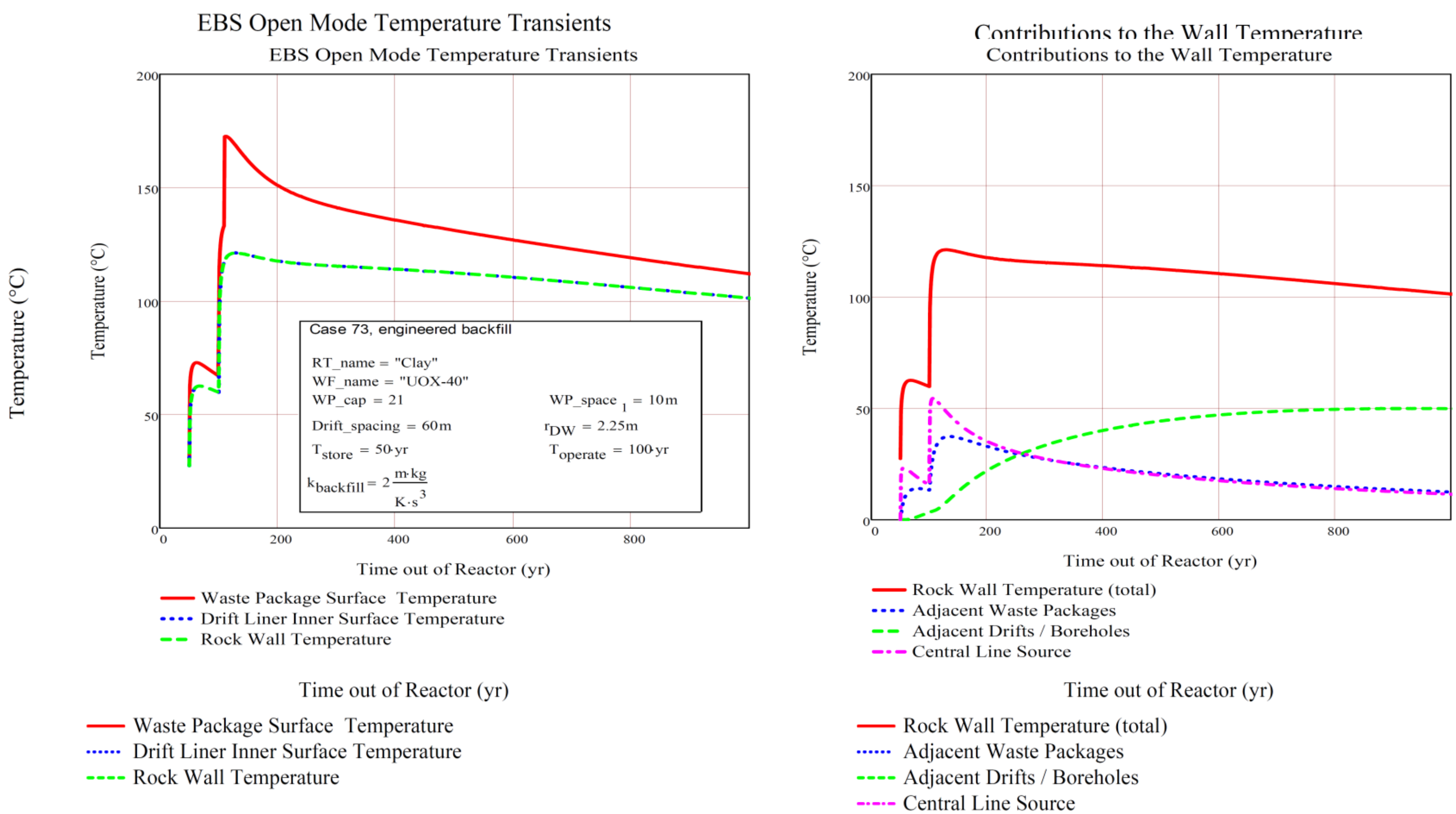
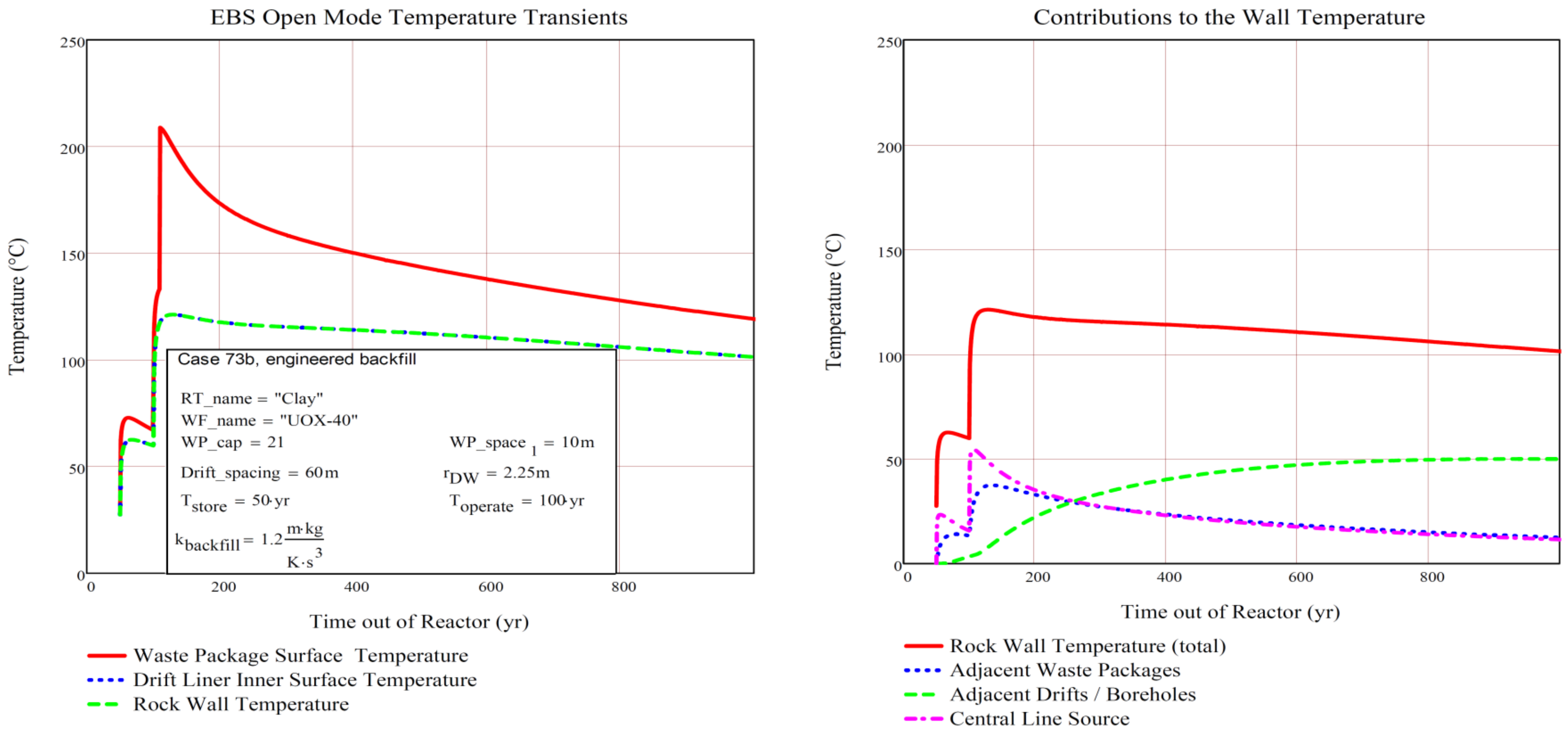


Figure B.5-2 Case 73– Backfill thermal conductivity 2 W/m-K, 60 m drift/borehole spacing, 50 yr ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9.



Waste Package Surface Temperature
Drift Liner Inner Surface Temperature
Rock Wall Temperature

Rock Wall Temperature (total)
Adjacent Waste Packages
Adjacent Drifts / Boreholes
Central Line Source

Figure B.5-3 Case 73b – Backfill thermal conductivity 1.2 W/m-K, 60 m drift/borehole spacing, 50 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9.

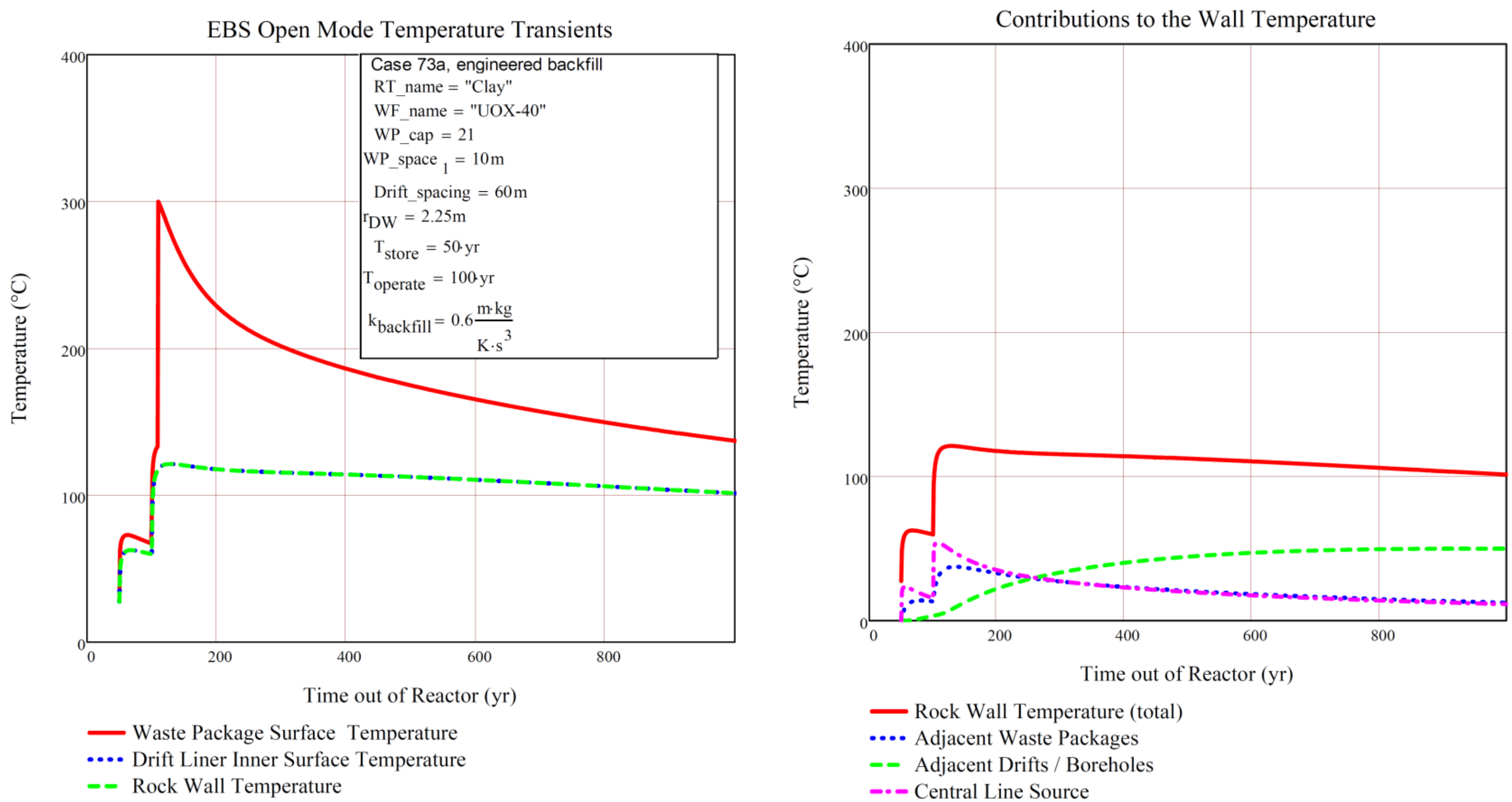


Figure B.5-4 Case 73a – Backfill thermal conductivity 0.6 W/m-K, 60 m drift/borehole spacing, 50 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9

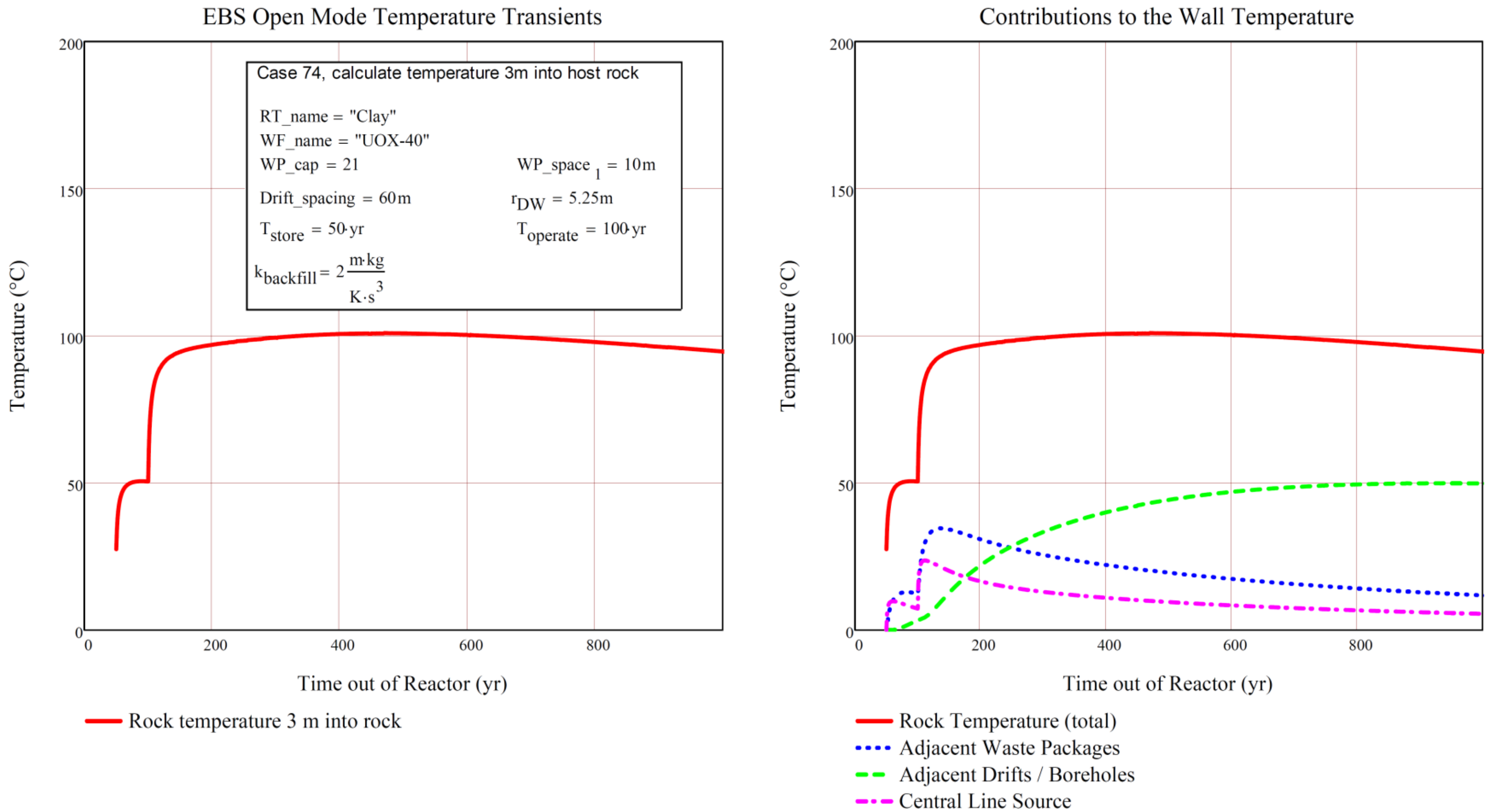


Figure B.5-5 Case 74 – Drift Wall radius 5.25 m (no backfill, 3 m into rock), 60 m drift/borehole spacing, 50 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9.

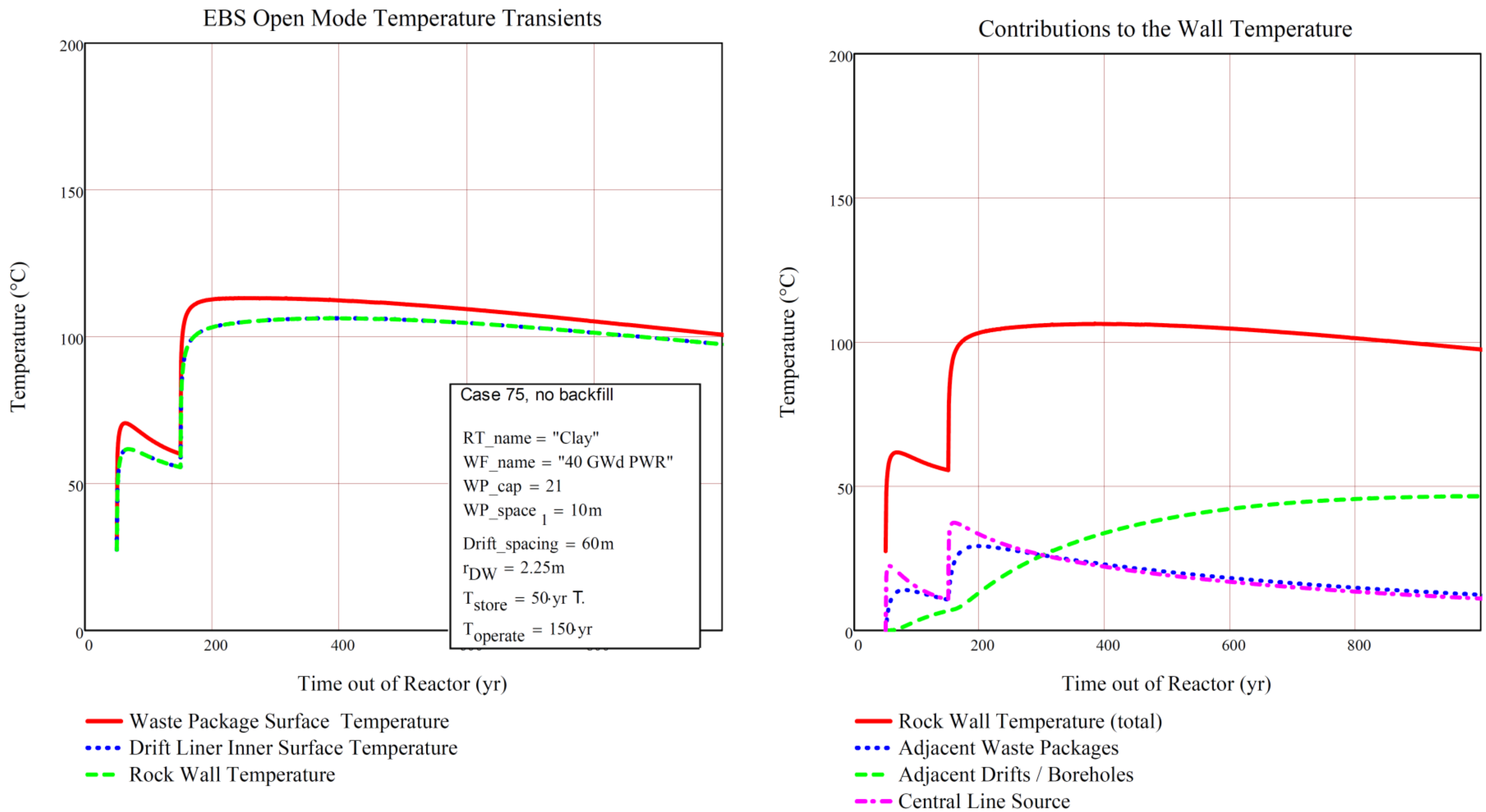
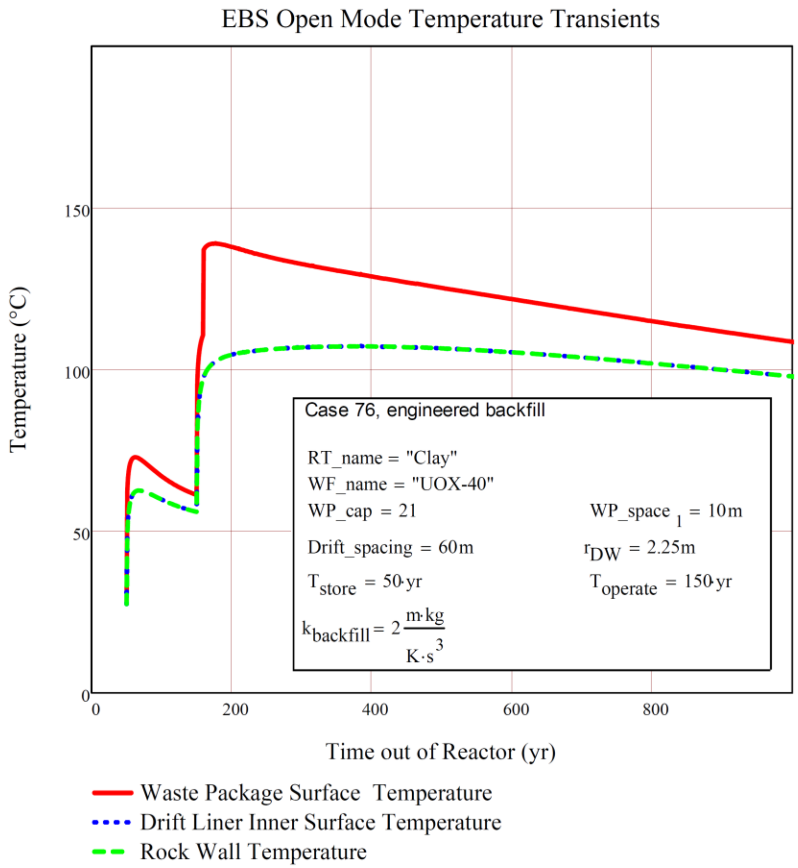


Figure B.5-6 Case 75 – No backfill, 60 m drift/borehole spacing, 100 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

Note: backfill not added until after 1000 years for closure, even though the thermal conductivity is listed on graph

For other parameters, see Base Case 21, Figure B.2-9



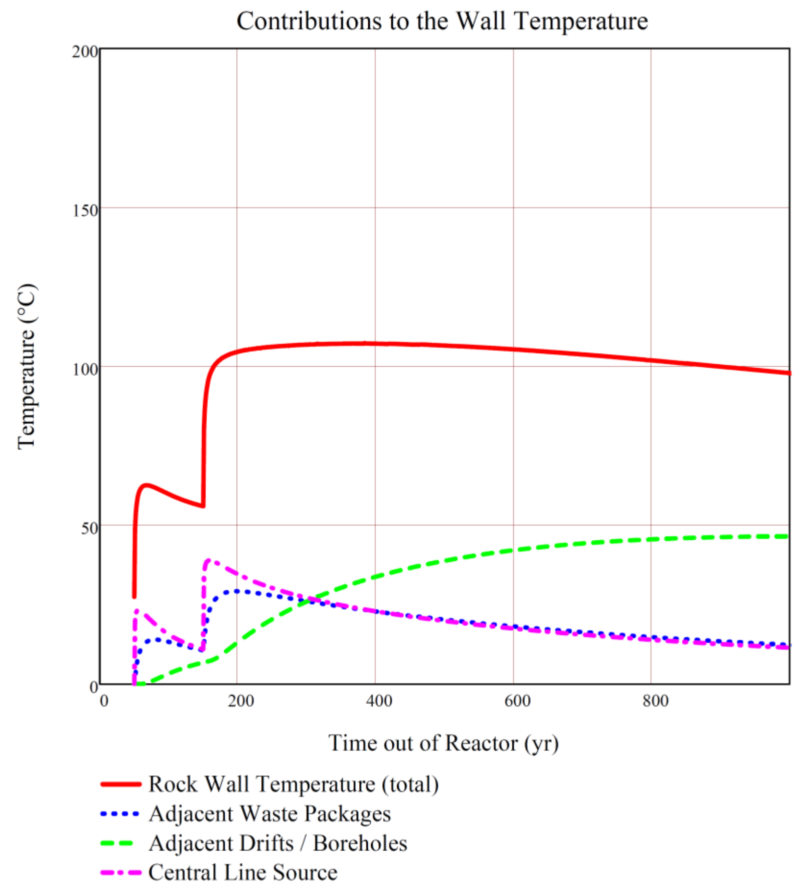


Figure B.5-7 Case 76- Backfill thermal conductivity 2 W/m-K, m drift/borehole spacing, 100 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9

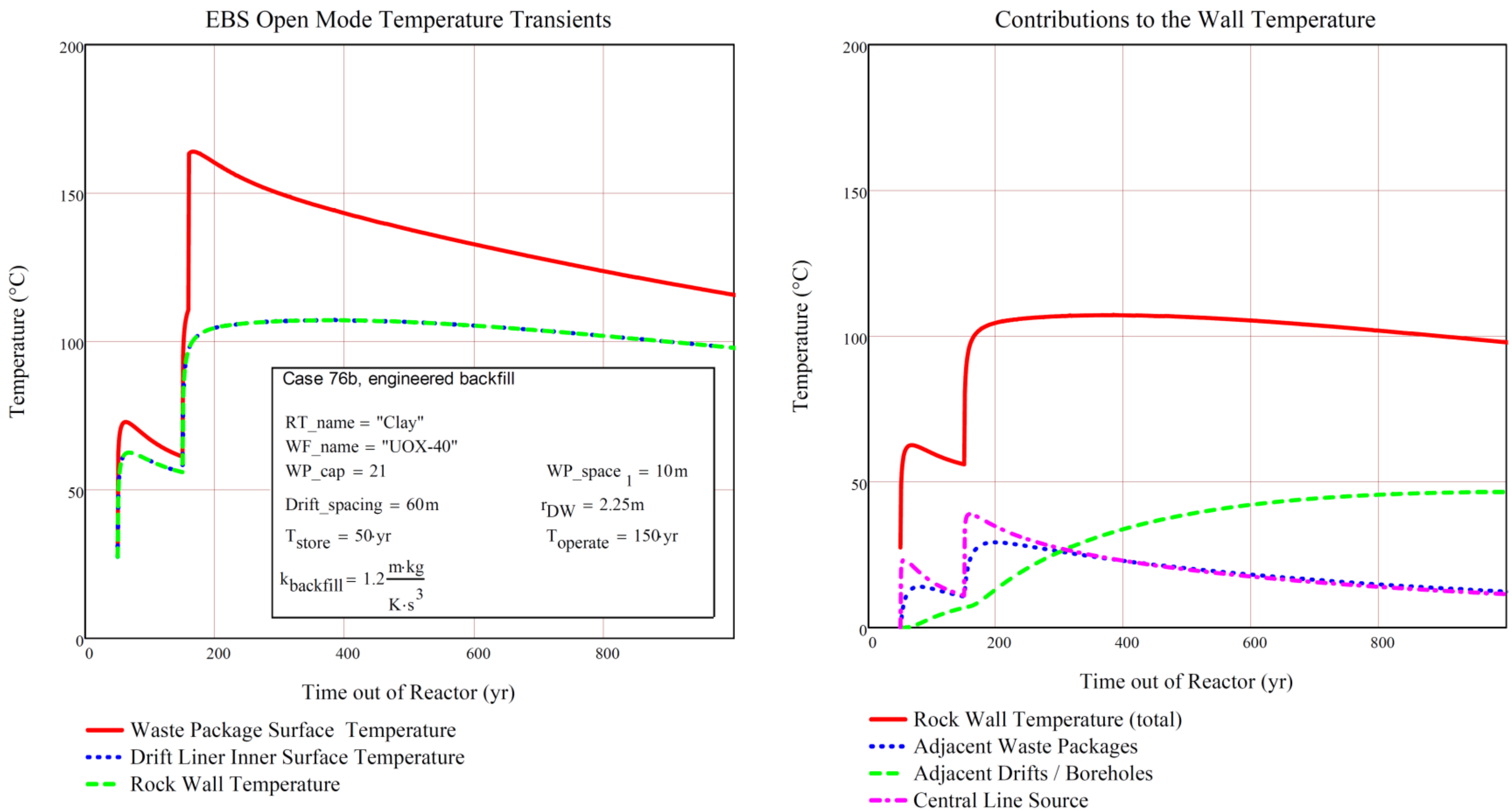


Figure B.5-8 Case 76b- Backfill thermal conductivity 1.2 W/m-K, m drift/borehole spacing, 100 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9.

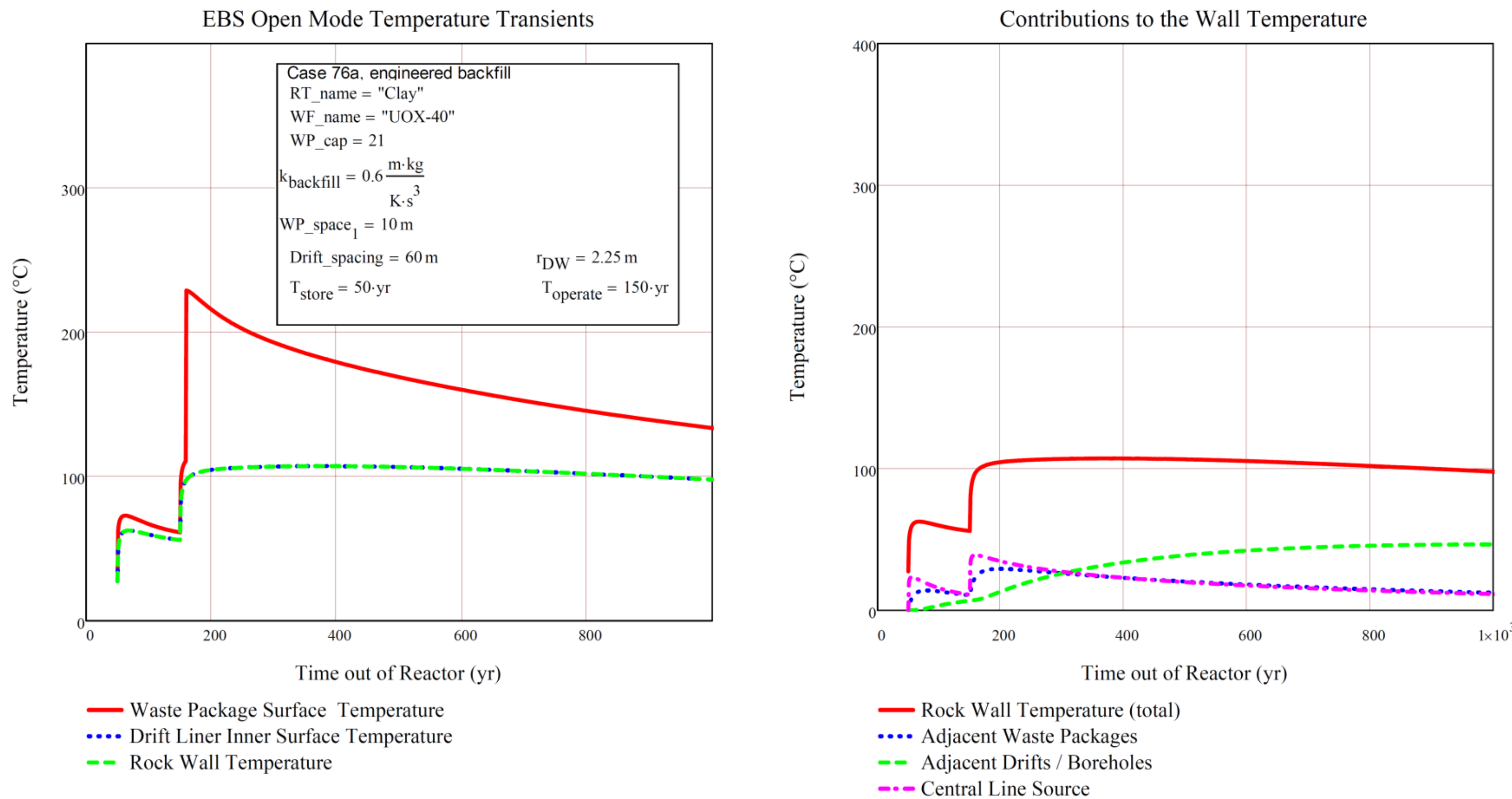


Figure B.5-9 Case 76a – Backfill thermal conductivity 0.6 W/m-K, m drift/borehole spacing, 100 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9

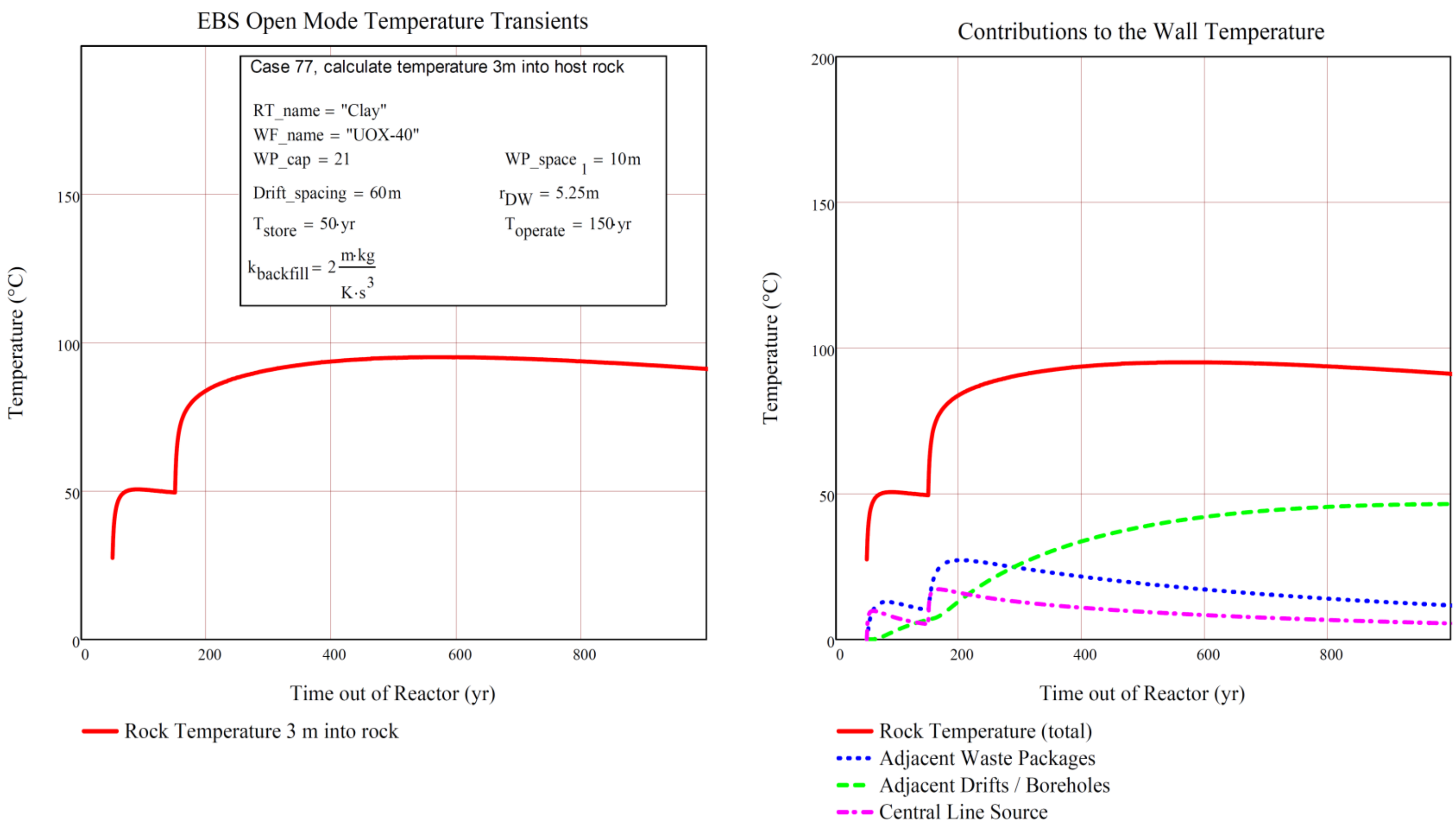
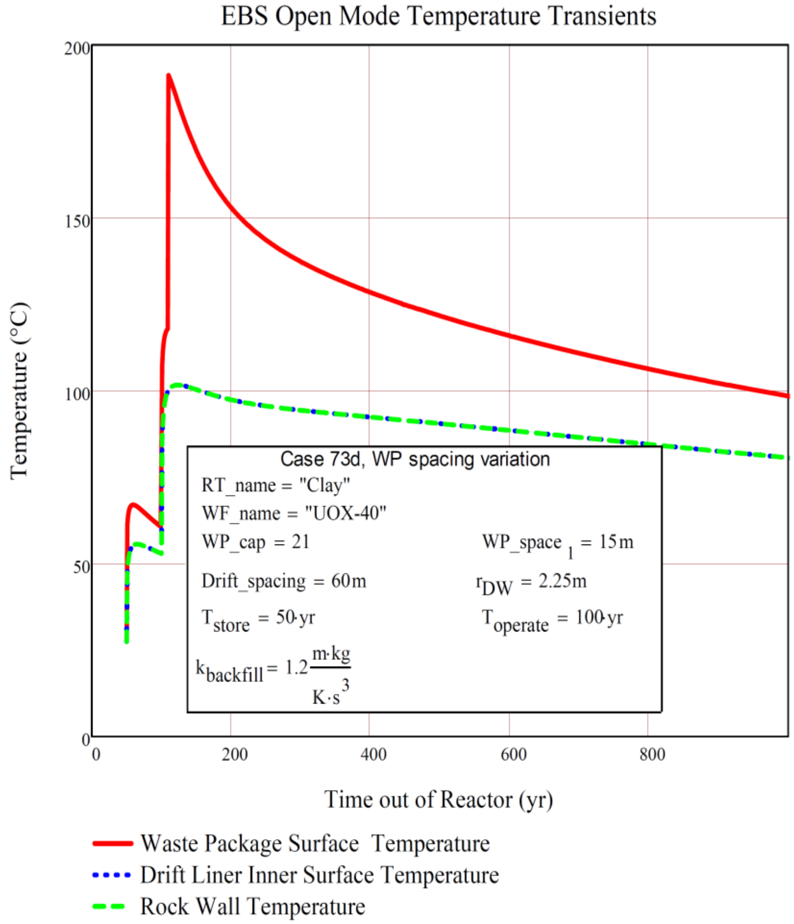


Figure B.5-10 Case 77 – Drift Wall radius 5.25 m (no backfill, 3 m into rock), m drift/borehole spacing, 100 yr. ventilation, Clay medium, 21-UOX, 40 GWd/MT, storage time of 50 yr

For other parameters, see Base Case 21, Figure B.2-9



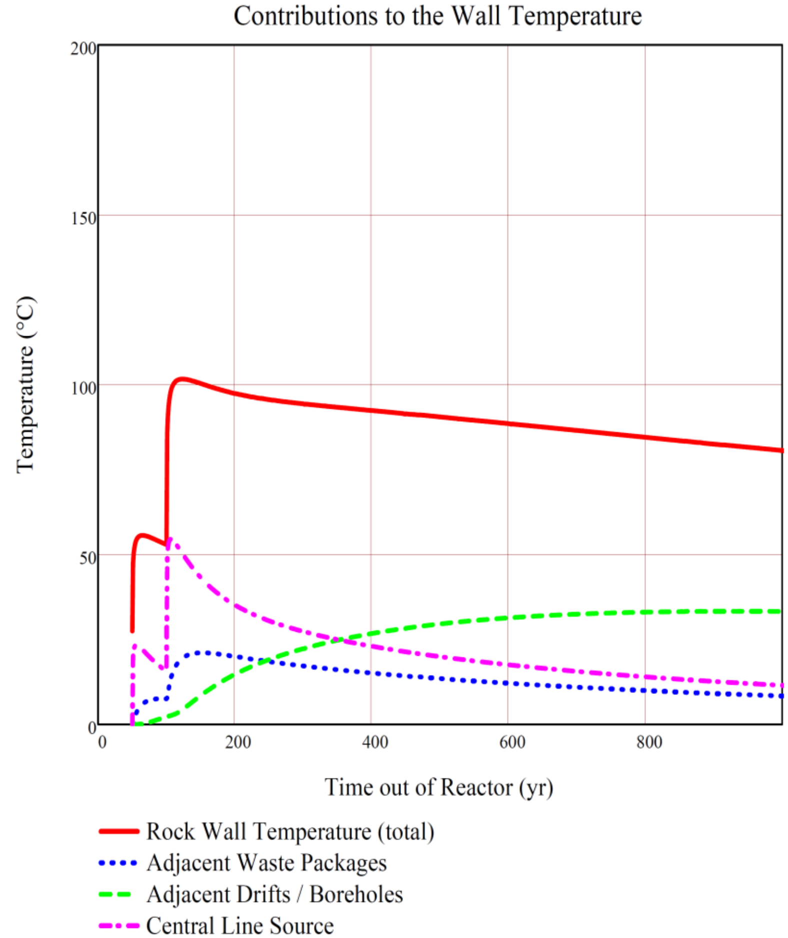
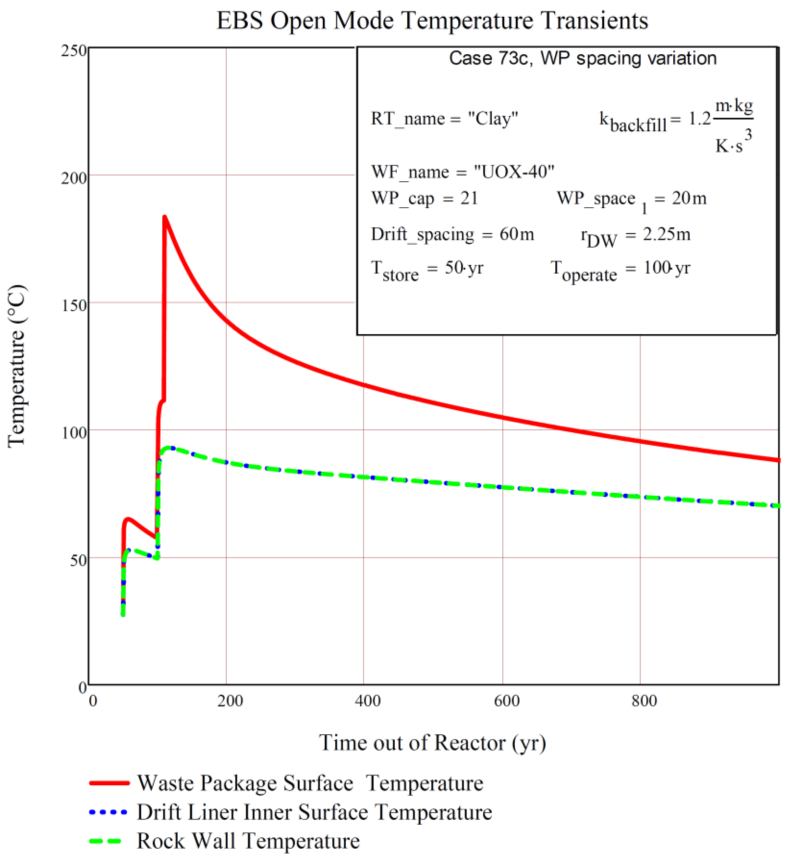


Figure B.5-11 Case 73d –15 m waste package spacing, backfill thermal conductivity 1.2 W/m-K, 60 m lateral (drift/borehole) spacing, and 50 yr. ventilation. Clay medium, 21-UOX WPs with 40 GWd/MT burnup and storage time of 50yr

For other parameters, see Base Case 21, Figure B.2-9.



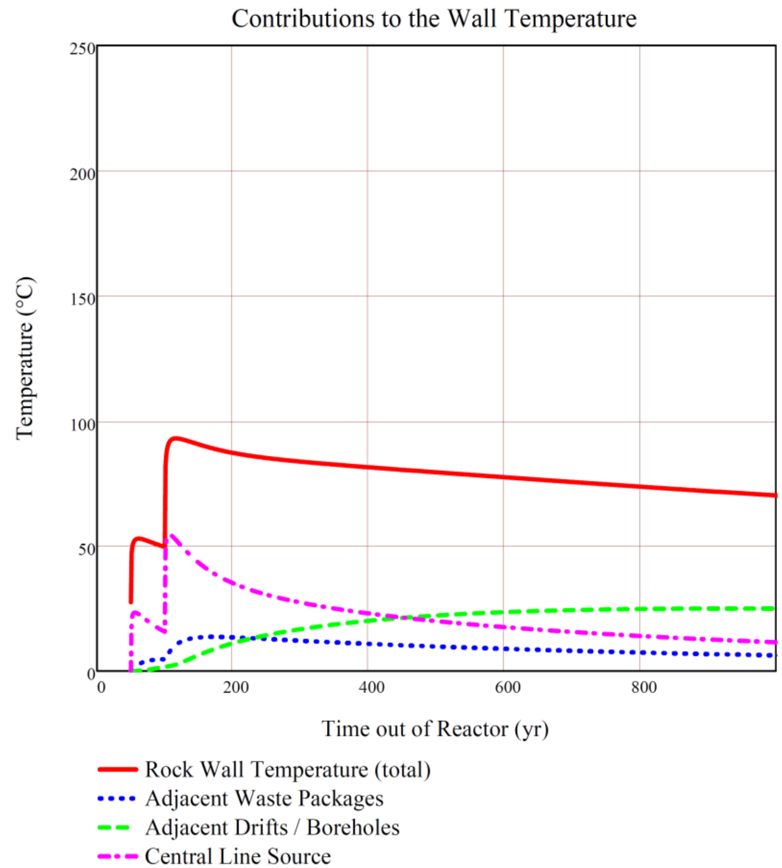


Figure B.5-12 Case 73c – 20 m waste package spacing, backfill thermal conductivity 1.2 W/m-K, 60 m drift/borehole spacing, and 50 yr. ventilation. Clay medium, 21-UOX WPs with 40 GWd/MT burnup and storage time of 50yr

For other parameters, see Base Case 21, Figure B.2-9.